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Generation IV Roadmap

Viability and Performance Evaluation Methodology Report

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1. BACKGROUND

The Generation IV Roadmap has identified nuclear energy systems that offer the greatest potential for meeting the goals of the Generation IV initiative. A system is defined as a complete nuclear system, consisting of the energy-producing plant and its associated fuel cycle. The Roadmap sets forth a long-term research and development (R&D) plan that will form a basis for international collaboration on those systems. The Roadmap process is expected to stimulate innovative and critical thinking on new nuclear energy systems that could, in the long term, offer substantial advances and breakthroughs.

Nuclear energy systems proposed for Generation IV are evaluated at different stages for their potential to meet the Generation IV goals. An initial evaluation, Screening For Potential, was conducted early in the Roadmap, in the Fall 2001. The Screening for Potential was carried out with relatively limited information about the proposed systems. The purpose of the Screening for Potential was to identify, for further consideration, those nuclear energy systems that meet the purpose and principles of the Generation IV initiative, and that have the potential for significant progress toward the established goals. The basic philosophy for the Screening For Potential was to avoid discarding systems with potential because of limited information available.

After the Screening for Potential, the technical working groups acquired additional information about the remaining systems and further assessed their performance characteristics. Moreover, the technical working groups defined sets comprising systems with engineering and performance similarities. To complete the Roadmap, the most promising systems or sets were evaluated again, in what has been referred to as the “Final Screening.” The purpose of the Final Screening was to select a small number of systems (6–8) offering the highest promise to meet the Generation IV goals and missions. The R&D needs for the systems selected in the Final Screening have been identified and categorized. The outcome of the Roadmap is the R&D Plan for the selected systems.

The recognition that future nuclear energy systems can potentially generate energy products other than electricity has been acknowledged in the Roadmap by defining Generation IV system missions beyond electricity production. Sustainability considerations have also resulted in defining Generation IV missions that emphasize resource or waste management in addition to energy products. The initial Generation IV missions identified during the Roadmap have been considered in the selection of the final set of systems for further development. The Generation IV missions will be further developed and defined during the system development phases.

The initial R&D phase, referred to as the Viability R&D, will address R&D issues that affect the viability of the selected systems to fulfill their potential as Generation IV systems. Another evaluation of the systems is planned at the conclusion of the Viability R&D Phase, with the object of further reducing the number of Generation IV candidates. The Viability R&D Phase will be followed by a Performance R&D Phase in which remaining systems will be further developed by researching issues, thereby demonstrating or improving the performance of the systems. A further evaluation will be performed at the end of the Performance R&D to select a few candidates for building a prototype, thus entering the demonstration phase prior to commercial deployment.

This document provides guidance on the methodology for conducting the Viability and Performance evaluations and suggests areas for further work in developing the evaluation methodology for assessing the systems for their performance with respect to the Generation IV goals. The Viability and Performance evaluations will be more detailed than the Screenings performed during the Roadmap, as the systems will be further developed and more system information, analysis and documentation will be available. The Viability and Performance evaluations should also address the performance of the systems in relation to specific missions. System characteristics or criteria for mission-specific performance may need to be developed when the missions have evolved sufficiently. The current document, while acknowledging its future need, does not provide a methodology for this mission-specific assessment.

NOTE: *Although this document uses the term "system," it is acknowledged that the use of the term "concept" to refer to a nuclear energy system has been in wide use in the Roadmap.*

2. PURPOSE

The general purpose of the Viability and Performance system evaluations is to further select the best systems to meet the objective of Generation IV, in terms of meeting the Generation IV goals and fulfilling the missions identified during the Roadmap (and possibly evolved between the completion of the Roadmap and the conduct of the evaluations). The Viability and Performance evaluation methods will also guide design decisions made during the Viability and Performance R&D periods, so the detailed designs further optimize the system performance in meeting the Generation IV goals.

More specific purposes, for each of the two evaluations, are:

Viability Evaluation:

1. Confirm that a system, as evolved during the Viability R&D phase, is viable and maintains high potential to meet Generation IV goals and fulfill its intended mission.

2. Assess progress made in the Viability R&D. Assess resolution of previously identified Viability R&D and current R&D plans.

3. Select systems for continued development into the Performance R&D Phase, based on their potential and the remaining R&D challenge.

Performance Evaluation:

1. Confirm that a system, as evolved during the Performance R&D phase, maintains high potential to meet Generation IV goals and fulfill its intended mission.

2. Assess progress made in the Performance R&D. Assess outcome of the Performance R&D tasks. Assess remaining development plan.

3. Provide the necessary information to advance a few systems to the Demonstration phase (construction of a prototype), based on the system performance in all Generation IV goal areas and the mission-specific characteristics.

Therefore, the Viability and Performance evaluations will need to address two primary subjects:

1. With the further development and information available for the systems, the systems need to be re-evaluated for their potential to meet the Generation IV goals. Although all systems were already estimated to have good potential to meet the goals during the Final Screening, an assessment of that potential needs to be performed again at the end of the R&D phases, as a confirmation of that potential and a measure of the uncertainty remaining. Specific missions for Generation IV systems will also be better defined at the time of the Viability and Performance evaluations, and the role of the systems in the missions needs to be reassessed.

2. Progress made during the R&D Phase must be evaluated. The outcome of the R&D needs to be assessed to determine whether the key questions have been answered and what important issues remain to be resolved. Of particular importance is the assessment at the end of the viability R&D, when a judgment is needed regarding the determination of the system viability or an estimate of the R&D (tasks, costs, schedules) remaining to confirm viability.

To meet the first objective, the evaluation methodology will need to assess system potential by applying an updated approach using criteria and metrics similar to those used in the Final Screening. In addition, a thorough assessment of the R&D issues and accomplishments will need to be completed in order to meet the second objective.

It must be emphasized that the Viability and Performance evaluations are only part of the planned development of Generation IV systems. The scope and purpose of the evaluations can significantly change, depending on how the overall Generation IV development continues and the evolution of the national policies within the Generation IV International Forum (GIF) member countries. The outcome of the R&D and in particular the R&D schedules will also dictate the need, timing and depth of the Viability and Performance evaluations, and the resulting decisions on whether to advance systems from Viability to Performance R&D, and from Performance R&D to the construction of demonstration facilities. With this awareness, the current document provides guidance on the methodology to conduct the Viability and Performance evaluations. The guidance emphasizes the important elements of the evaluation at the end of the different R&D stages.

3. PROCESS

The current Roadmap specifies the R&D plan for development of the systems selected by the Final Screening and an approximate R&D schedule for resolving the technical challenges. The process for evaluating the results and progress accomplished during the R&D stage is not yet defined. It is anticipated that the DOE and GIF will establish peer review groups to monitor and evaluate the development of the systems and provide advice on the selection among design options within specific systems, coordination and prioritization of crosscutting R&D between systems, and decisions to advance R&D efforts from the Viability to the Performance phase, and from the Performance to the Demonstration phase. The detailed process will be elaborated as the development of the Generation IV evolves.

For the purpose of the methodology guidance, it is assumed that the system development teams will document the design status, supporting reference documentation, and R&D outcomes. The information will be provided to a system review group that will assess the system and the R&D progress. The review group will provide recommendations to the DOE and GIF. The review group will have expertise in all the goal areas and will include international representation spanning industry, academia, and research laboratories.

If the development schedules for the different systems are parallel, it is possible that a review group will be formed at the end of the Viability and Performance R&D Phases. On the other hand, if the different systems are on significantly different development schedules, DOE and GIF may choose to perform a review of each system separately, when it reaches its own R&D milestones (i.e., completion of viability and performance development phases). The methodology guidance provided in this document is intended for use by the system review group(s) and can be used for either development approach (simultaneous decisions across all systems, or independent advancement of individual systems.)

4. VIABILITY AND PERFORMANCE EVALUATION: METHODOLOGY

This section provides guidance on the methodology for the system evaluations to be conducted at the end of the Viability and Performance R&D stages. Two main subjects must be assessed for the systems when they reach key milestones in their development:

- System potential to meet the Generation IV goals and the mission-specific requirements.
- Assessment of system R&D. This includes an assessment of the progress accomplished during the previous R&D phase, and the R&D plan for completing the development of the system.

To assess the system potential, an evaluation similar to that performed for the Final Screening, based on a set of criteria for each of the goals, is proposed. The definite set of evaluation criteria will need to be developed at the time of the evaluation, but a proposed set, based on a modification of the Final Screening criteria (to account for the development of further system information) is provided in Appendix A. Mission-specific requirements, which must be established at a future date, can either be translated into additional criteria or into a set of relative weights of the existing goal-related criteria.

The assessment of R&D must be based on the R&D plan established at the beginning of the R&D program, and must include a detailed evaluation of the resolution of the key issues identified in the R&D plan. The remaining development must be evaluated in terms of importance and impact on the system performance, costs, and schedules. While there is no specific methodology for this assessment, guidance on a systematic approach is provided, based on the technology readiness levels (see Section 4.3.)

4.1 Overall Approach

As in the Final Screening, the basic principle for the selection of the preferred Generation IV systems is based on the premise that the most desirable systems are those that offer a high potential to meet the Generation IV goals and have a reasonable risk associated with achieving that potential. In other words, the selection process is a trade off between the system potential and a measure of uncertainty about that potential, as represented by the progress accomplished in resolving key technical issues, and the remaining technology gaps.

The two stages of R&D, which are distinguished by the characteristics and the nature of the R&D as the system design development matures, are defined as follows:

1. *Viability R&D.* That R&D necessary for proof of the basic concepts, technologies, and processes at relevant conditions. Potential "show-stoppers" are identified and resolved in this phase. The information generated at this stage is sufficient for the conceptual design stage of a prototype.

2. *Performance R&D.* That R&D necessary for engineering-scale verification of processes, phenomena, and material capabilities in representative conditions. The information generated during this phase is sufficient to allow a detailed design and performance specification for prototype or demonstration facilities, and allow beginning the development of a certification application.

The endpoints of the Viability and Performance R&D Phases, with the listing of the system design information that should be available at the time, is provided in Table 1.

Table 1. Endpoints for the Viability and Performance R&D phases.

Viability Phase	Basic concepts, technologies and processes proven at relevant conditions; potential technical "show-stoppers" identified and resolved.	
	System has advanced to the point that the following information has been developed: • Conceptual design of nuclear island • Simplified Probabilistic Risk Assessment (PRA) to identify the contribution to the risk of all the transients and accidents resulting from internal and external events, for all facilities and all operating modes and assess their approximate probabilities; identification and ranking of the phenomena that govern the system transient response • Demonstration that separate effects experimental data are available, or are planned for, that closely replicate the scaled boundary and initial conditions for the dominant phenomena with minimal distortion • Description of the integral test facilities and their instrumentation planned to validate system transient response models, preferably at prototypical scale • Nominal interface requirements for power and support systems • Basic fuel cycle process flow sheets established by testing at reasonable scale • Pre-conceptual design of process facilities, with established pathways for disposal of all process waste streams • Simplified environmental impact statement for system • Preliminary Business Plan based on conceptual design • Preliminary safeguards and security strategy discussing intrinsic proliferation resistant features and identifying necessary extrinsic controls and physical protection needs • Consultation with regulatory agency on safety approach and framework issues.	
Performance Phase	Engineering-scale verification of process, phenomena, and material capabilities in prototypical conditions.	
	System has advanced to the point that the following information has been developed, in addition to the information developed during the Viability R&D phase: • PRA • Separate effects and integral test data available for code validation • Validation of analytical tools • Conceptual design sufficient to show interface requirements for power and support systems • Fuel cycle process flow sheets validated at scale sufficient for commercial demonstration • Conceptual design of process facilities, with validated acceptability for disposal of all process waste streams • Environmental impact statement for system • Detailed Business Plan for system, including fuel cycle facilities • Safeguards and security strategy for system, including cost estimate for extrinsic features and physical protection • Performance requirements and design information for nuclear island, sufficient for procurement specifications for construction of a prototype or demo plant • Preapplication meetings with regulatory agency	

The Demonstration phase will follow the Performance R&D Phase, and may require the construction of prototype or demonstration facilities, and involve partnerships between R&D and commercial (vendors, utilities) organizations. The system design will be optimized during that phase.

4.2 System Evaluation with Respect to the Generation IV Goals

A modification of the basic approach used in the Final Screening during the Roadmap is proposed as the method for evaluating system potential. Although the systems selected at the Final Screening showed good potential to meet the goals, it is necessary to evaluate that potential when R&D has been performed and more information is available (see Table 1). The additional system design information and the results of the R&D should permit a much better evaluation of the system against Generation IV goals.

The Generation IV technology goals are still to be represented by a set of representative criteria and metrics. The concepts should be evaluated against those criteria. A probability-based approach is again proposed for expressing the potential of the systems and the uncertainty associated with that potential. Probability distributions will be used to represent the potential and uncertainty of a system with respect to each criterion.

The proposed criteria (Appendix A) are based on the criteria used in the Final Screening, but modified to take advantage of the more abundant information available for the system, design and performance. Because of this additional information, the metrics proposed are more of a quantitative nature than at the time of the Roadmap screenings. Appendix A provides the suggestions for criteria and metrics divided into goals. It must be noted that for some goals it has been possible to identify a very clear criterion and associated metric as truly representative of the goal. Further work is needed to establish truly representative and comprehensive criteria and metrics for other goals, notably for Proliferation Resistance and Physical Protection. In such cases, Appendix A provides guidance on the key representative issues under the goal.

At the Viability and Performance evaluations, the system "scoring" is de-emphasized. At the time of the Final Screening, when many systems were being evaluated at the same time, there was a clear need for ranking the systems to identify the most promising for further development. Fewer systems will be assessed at the Viability and Performance evaluations; furthermore, the assessments may not occur simultaneously, depending on the R&D program schedules for each system.

Therefore, the emphasis during these evaluations must be in assessing the evolution of the system potential to meet the goals (and mission-specific requirements) as a result of the R&D outcome and the additional development of the system design.

The evaluation of the system for performance with respect to the advanced light water reactor (ALWR) reference used in the Final Screening is de-emphasized in the Viability and Performance evaluations. During the Final Screening, systems were evaluated for their potential to improve performance beyond the current generation of nuclear systems, primarily in areas where quantitative metrics could not be identified. A more extensive use of quantitative scales is suggested for future evaluations, thus somewhat obviating the need for the establishment of an ALWR reference. To place the system performance in perspective, a comparison to a reference will still be informative. Thus, it is recommended that the system evaluation be compared to its own previous evaluation, and when feasible, to the latest deployed nuclear systems (NP2010 if applicable, or ALWR).

For each criterion and metric, the review group(s) will need to evaluate the potential of the system as well as the uncertainty about that potential. The assessment will be assigned in a single step in the form of a probability distribution that represents the range of potential of the system with respect to the criterion considering all sources of uncertainty. The systematic identification of sources of uncertainty, and assessment of the sensitivity of the probability distributions to these uncertainties, will guide the prioritization of research to reduce the uncertainties and narrow the probability distributions.

In addition to the inherent uncertainty about the performance of the system, uncertainty about the outcome of the R&D is reflected in the probability distribution. The upper range of the distribution assigned to a system represents the performance potential of the system that would be realized if all the remaining R&D to validate the design performance assumptions proves to be successful, while the lower range represents performance that would be obtained should the assumptions be proven to be invalid by the remaining R&D. The best estimate value is based on the outcome of the R&D completed at the time of the evaluation.

Unlike the Final Screening, where a relative comparison of numerous systems was needed, there is no need in the Viability and Performance evaluations for the use of figures of merit to represent in a single value the assessment against multiple criteria or goals. However, depending on the identified mission-specific characteristics or criteria, it may be necessary to develop a figure of merit in assessing the role of systems in fulfilling specific missions.

4.3 System R&D Evaluation

The degree of development of the system can be expressed in terms of its technology readiness level (TRL). The use of a TRL provides a single parameter characterizing the state of development of a particular technology. For the purpose of the Roadmap, five technology development levels were defined to identify the endpoints for the Viability and Performance R&D (see Table 2). It must be noted that a finer subdivision into more TRLs is possible and may be used in the future when assessing the level of development of a particular system.

Table 2. The TRL levels defined in the Generation IV Roadmap context.

Level	Title	Description
TRL1	Basic research in new technologies	Scientific research begins to be translated into applied R&D; no experimental proof exists yet
TRL2	Proof of phenomena	Analytical and experimental demonstration of critical function and/or characteristic proof of concept
TRL3	Technology development	Small-scale (laboratory) demonstration in a relevant environment
TRL4	Proof of practicality	Subsystem or separate effects test completed in representative conditions; concept is proved to be practical in representative conditions
TRL5	Proof of concept	Large-scale (integral facilities) tests in representative conditions

The Viability R&D is expected to take the system through a TRL3. By the end of the Performance R&D phase, a system should have been developed to a TRL5. The endpoints and expected documentation for the two R&D Phases have been summarized in Table 1 above.

During the Roadmap the technical working groups and the crosscut groups have defined the R&D needed for the selected nuclear systems to reach the R&D Endpoints and the desired Technology Readiness Level. The key viability and performance technology gaps have also been defined. At the time of the Viability evaluation, the R&D outcome and results will need to be contrasted with the Roadmap R&D Plan.

4.3.1 Viability Evaluation

The review groups must determine if all the technology gaps affecting viability, as identified in the Roadmap R&D plan, or further identified during the R&D period, have been resolved, and if the desired TRL3 has been completed. The suggested documentation (Table 1) will assist in determining the level of development. Those items that had been identified as potential "show-stoppers," are of particular importance. Resolution of show-stopping items must be carefully documented, as well as the existence of any remaining ones or the appearance of new ones identified during the viability R&D.

The review group must assess a proposed plan for completing the R&D for viability technology issues that have not been satisfactorily resolved (either because it was originally on a longer schedule or because difficulties have arisen during the performance of the R&D).

An update of the R&D scope report must be prepared for each system. The report must clearly identify any remaining areas where viability needs to be researched, the proposed plan, including costs and schedules, and the plan for performance R&D.

The information related to the R&D assessment can be summarized in a table, as was done during the Roadmap. This table must indicate the progress made in the viability R&D items, clearly identify remaining viability issues and potential show-stoppers, contain a reference to the R&D plan to resolve these issues, and give details about the costs and schedules for the remaining R&D.

The lack of resolution of viability issues or the appearance of new ones is an important factor for the possible termination of a system R&D effort. Therefore, the proper identification and documentation of remaining viability issues and their plans for resolution are crucial for the decision-makers to determine whether to continue with the development of the system.

4.3.2 Performance evaluation

At the end of the Performance R&D another assessment of the status of the technology is needed. The development must have reached the desired TRL5 before proceeding with the demonstration and commercialization. The starting point will be the updated R&D plan prepared at the end of the viability phase. Particular attention should be paid to those viability issues that have not been resolved at the time of the previous evaluation. Additionally, remaining viability issues are expected to have a high likelihood of successful resolution. No viability issues should remain unresolved at the end of the Performance R&D phase. The progress made in the performance R&D tasks must also be assessed. Remaining uncertainties must clearly be stated, as they will have a big impact on the decision to proceed into the technology demonstration phase.

If R&D has been performed to improve performance in goal areas where a system has shown some weakness at the evaluation for potential during the Final Screening, the effect of such R&D must be reflected in the evaluation of potential.

With the additional information developed regarding the design of the system and the outcome of the R&D, detailed costs estimates and schedules for the demonstration (cost and schedule of a prototype system) phase must be produced by the system developers and evaluated by the review group(s). Industrial partners should be fully involved at this stage of the evaluation, and the selection of preferred systems at the end of the Performance R&D phase should include input from industry.

4.3.3 Periodic Reviews

Even though two major evaluation points are recognized at the end of the Viability and Performance R&D stages, it is anticipated that more frequent reviews of the R&D progress will be performed during the R&D phases (for example, at funding planning exercises). The Viability and Performance R&D assessments will build on the periodic review findings. The periodic reviews can be expected to uncover any major problems or show-stoppers that may appear in the development of a system, such that no major surprises will be expected during the more detailed Viability and Performance evaluations.

Selected systems may be on different schedules to arrive at the desired viability and performance technology readiness levels. For systems satisfying crucial viability issues early, performance R&D should proceed to prevent a loss of momentum in the development process. It may be desirable to perform the Viability evaluation for early systems as soon as the Viability R&D is complete. However, the pace and funding of subsequent R&D should be established with consideration that other systems may prove superior at the end of their Viability phase.

4.4 System Selection

In general, the selection of the preferred systems should be based on the trade-off between the (better-evaluated) potential of the systems to meet the Generation IV goals and the remaining R&D challenge and costs to develop the system to commercialization. The most desirable systems are those that offer very high potential with low remaining R&D costs, while fitting the requirements of the intended missions.

The down selection to fewer systems will depend on multiple considerations. As has been experienced in the Final Screening, the relative ranking of the importance of the Generation IV goals, and the assessment of different systems potential to meet them, depend on specific mission characteristics and national assessments and priorities. While the Generation IV goals are broadly shared by the GIF countries, characteristics to fulfill a specific mission, R&D scope, and national assessments among GIF countries have substantial impacts on the selections. It can be anticipated that the selection of systems at the end of the Viability and Performance phases will similarly be influenced by a number of factors other than the system potential and the technology readiness level.

Factors expected to be of particular significance for consideration in the system selection for each of the evaluations are:

Viability Evaluation:

- Changes in system potential to meet Generation IV goals
- Relative importance of the goals, which may evolve in time and geographically
- Remaining viability issues and R&D plan to resolve them
- Significance and cost of remaining R&D
- Applicability of R&D to multiple systems
- Evolution of specific missions

- Evolution of national interests in GIF countries
- Number of systems that can be supported for development.

Performance Evaluation:

- Changes in system potential to meet Generation IV goals
- Relative importance of the goals, which may evolve in time and geographically
- Remaining performance issues and plan to address them
- Significance and cost of remaining R&D
- Cost and schedule of demonstration facilities, if needed
- Evolution of specific missions
- Evolution of national interests in GIF countries
- Number of systems that can be supported for demonstration
- Energy market conditions
- Industrial interest in technologies under consideration.

All these issues will need careful consideration to select among the remaining Generation IV system candidates. In general, viability issues should have been resolved as early as possible. If some remain at the end of the performance R&D, the system should not be given further consideration. On the other hand, a remaining viability issue may not be sufficient reason for exclusion at the end of the Viability evaluation if a reasonable plan exists to resolve it and the other factors (system potential, interests, mission fulfillment, etc.) are rated positively.

5. RECOMMENDATIONS FOR DEVELOPMENT IN EVALUATION METHODOLOGY

With the exception of the Proliferation Resistance and Physical Protection (PR&PP) goal area, opportunities for R&D for system evaluations have been identified within the crosscut groups (Safety and Reliability and Economics Crosscut groups, in particular) and are listed in the corresponding sections. The current section will therefore primarily address evaluation methodology R&D with regards to PR&PP.

As the definition of specific missions for Generation IV systems evolves, the Viability and Performance evaluations will need to assess the performance of the systems for the specific missions. The mission-specific assessment will need to be incorporated into the evaluations. This will require either the development of mission-specific criteria, or the development of a mission-dependent set of relative weights among the goal-related criteria. This is not expected to require a separate method, but rather a variation in the implementation of the proposed methodology.

5.1 Sustainability

The Fuel Cycle Crosscut Group has identified R&D issues related to fuel cycles, such as the use of symbiotic systems, that will affect sustainability considerations. However, no specific needs on sustainability evaluation methods have been identified. Quantitative criteria and metrics for evaluating systems against both SU1 and SU2 have been proposed for future system evaluations, with the exception of environmental impacts. However, enough guidance exists for the performance of a preliminary environmental impact report to qualitatively evaluate systems with respect to existing deployed systems. Therefore, no further development of evaluation methods is deemed necessary in the sustainability area, as defined in the Generation IV Goals, for the future evaluation of Generation IV systems. However, it is recognized that some of the GIF countries define sustainability in broader terms. Some additional work may be necessary to portray the evaluation outcomes in a broader sustainability framework.

5.2 Safety and Reliability

The Risk and Safety Crosscut Group (RSCG) report describes some R&D needs for system evaluation on this subject. The primary system evaluation in this area is based on the development of a stepwise PRA, developed to the level of detail available of the different evaluation stages. The RSCG has identified a few areas of particular relevance to Generation IV systems that will need further development. Their recommendations are summarized as follows:

Safety and Reliability Viability Crosscutting R&D:

- Safety system optimization, modeling, and coherent and simplified PRA
- Emergency planning methods.

Safety and Reliability Performance Crosscutting R&D:

- Licensing and regulatory framework
- Radionuclide transport and dose assessments
- Instrumentation, control, and the human-machine interface

- Reactor physics and thermohydraulics
- Risk management
- Operation and maintenance
- Human factors.

The development of a simplified PRA and how its step-wise application relates to the SR1, SR2 and SR3 goals will have a direct impact on the Viability and Performance evaluations, as the basis for the safety and reliability criteria will be in the use of the simplified PRA. The outcome of the R&D on emergency planning methods may also affect the approach to the evaluation of SR3 and will therefore have a direct impact on the methodology.

In general, the remaining safety and reliability crosscutting issues identified above, under Performance crosscutting, will result in an improvement in the assessment of safety issues for a system, and reduce the uncertainty about the safety margins. Thus, R&D in these areas will result in a better evaluation of the system, although it will not affect the evaluation methodology. The EMG is in agreement with the guidance provided by the RSCG.

Detailed information about the recommended safety and reliability R&D is contained in the RSCG R&D scope report and summary table.

5.3 Economics

The criteria and metrics for Economics (EC) recommended for future evaluations are the same as those used in the final screening. However, the Economics Crosscut Group (ECG) R&D scope report provides additional guidance on models to evaluate systems for those criteria (models for estimating different cost components).

The following items have been identified for further EG crosscutting R&D:

EC Viability Crosscutting R&D:

- Construction-Production cost model
- Fuel cycle economics
- Nonelectricity production
- Research, development, demonstration and deployment optimization models.

EC Viability and Performance Crosscutting R&D

- Optimal plant size model
- Integrated nuclear energy system model.

While the criteria recommended in Appendix A will not change, the models used to evaluate a system against those criteria will be improved as a result of this R&D. Therefore, all the items listed above will impact the Viability and Performance evaluations. In particular, the economic models used in the Final Screening were incomplete in important Generation IV issues such as the economics of the back end of the fuel cycle, the assessment of alternative (nonelectricity) energy products, and the effect of modularity and plant size. The recommended EC crosscutting R&D should provide the basis for an improved assessment of these items in the Viability and Performance evaluations. The Evaluation Methodology Group (EMG) is in agreement with the guidance and economic models identified by the ECG. More detail on the ECG recommendations can be found in the ECG R&D scope report.

It is also the recommendation of the EMG that a business plan for the Generation IV systems be documented before future system evaluations. The guidance for the business plan provides information on accounting for alternative energy products and on the economic assessment of the systems on their ability to fulfill a specific mission.

5.4 Proliferation Resistance and Physical Protection

The methodology developed by the EMG during the Roadmap provided only a limited evaluation of PR&PP. An improved PR&PP evaluation methodology is needed to assess nuclear energy systems in the future. Because there has not been a crosscut group specifically addressing PR&PP, this subsection provides input on the recommended technology R&D relevant to this goal area, followed by recommendations on R&D in evaluation methods. Guidance on conducting the Viability and Performance evaluations is provided under the Proliferation Resistance and Physical Protection section of Appendix A to this document.

The endpoints and system documentation at different stages in the system development, as listed in Table 1 above, indicate that a preliminary Safeguards and Security strategy should be developed for each candidate system during the Viability R&D Phase of Generation IV. The document describing this strategy will by necessity be conceptual and schematic in nature, reflecting the state of development of the nuclear energy system during the Viability stage. It will address the vulnerabilities foreseen for each system in relation to five security areas that can be distinctly identified. The five security areas are listed in Table 3 and described in more detail in Appendix A to this document. During the Performance R&D phase of Generation IV, the preliminary strategy document should evolve into a final strategy document, defining the specific responses foreseen to ensure that the risks presented by each candidate system are minimal.

During both the Viability and Performance phases, the preliminary/final strategy document will be reviewed against a set of criteria and metrics related to intrinsic and extrinsic measures defined for the purposes of addressing the five security areas. The elements of the criteria/metrics and the identification of specific criteria and metrics represent one area for R&D, as presented below. The evaluation process is envisioned to rely upon periodic reviews by expert panels, using an assessment methodology that would be established in a second area of R&D, also presented below.

Some aspects of the vulnerability of any nuclear energy system in any of the five security areas and the manner in which the issues are addressed, in some specific areas, can potentially be matters of high sensitivity and information is normally restricted and made available only on a need-to-know basis. It will be necessary to employ existing security arrangements to protect such information; for some GIF participants, it may be necessary to upgrade national protective measures in this regard. All parties to collaborative R&D programs under the GIF will need to establish appropriate arrangements for sharing the information essential for the collaboration to be successful. It is likely in such cases that some categories of information will not be shared, and for special conditions to apply to sharing even less sensitive information.

Table 3. Template for compiling intrinsic and extrinsic barrier elements for five security areas during the viability and performance phases of Generation IV.

Security Area	Viability Phase		Performance Phase	
	Intrinsic Measures	Extrinsic Measures	Intrinsic Measures	Extrinsic Measures
Nuclear weapons proliferation: diversion of nuclear material from declared flows or inventories; undeclared production; replication of facilities/equipment.				
Nuclear explosive devices: theft of weapon-usable material for the construction of one or more nuclear explosive devices.				
Radiation dispersal devices: Theft of hazardous radioactive material for dispersal at a designated location				
Facility sabotage: Destruction of facility, mis-operation or disabling of critical safety systems causing the release of hazardous radioactive material.				
Transport sabotage: Intentional breach of transport containment causing the release of hazardous radioactive material.				

Against the necessity to control and protect such sensitive information, attention should also be given to the need for a sufficient degree of transparency so as to accurately inform the public on the general measures addressing the potential security threats and the level of protection provided through such means.

Taking into account the information needed in the Safeguards and Security Strategy, the R&D program relevant to the topic of Proliferation Resistance and Physical Protection should be directed in three areas. The first area pertains to technology R&D to be carried out in the development of each Generation IV system under consideration. The remaining two areas are specific R&D needs for PR&PP evaluations.

5.4.1 Topic 1: Elements of the Safeguards and Physical Protection Strategy/Plan

R&D is recommended under the Viability and Performance phases of Generation IV to be carried out by the GIF proponents of each candidate nuclear energy concept:

1. The types, amounts and locations of weapon-usable nuclear material, other nuclear material from which weapon-usable material could be created (through enrichment, reprocessing or irradiation followed by reprocessing), and hazardous radioactive material should be defined in the context of each concept and the anticipated provisions for its future deployment over the life cycle anticipated.

2. R&D should be carried out to determine means to protect key reactor or fuel cycle facility technology against unintended use, and related systems, equipment and materials against unauthorized replication.

3. For all materials at each stage of the fuel cycle, potential vulnerabilities should be identified separately in relation to each of the five specified security areas. For each vulnerability identified, R&D should be carried out to decrease the attractiveness of the material for diversion or theft, or to make it difficult to disperse the material, as appropriate.

4. For each material form that would be used or produced in a Generation IV nuclear energy system, R&D should be carried out to define and increase the intrinsic and extrinsic protection afforded against diversion, theft or dispersal by exploiting or introducing chemical or physical features or through the use of radiation barriers to decrease potential vulnerabilities.

5. For solution processing systems, such as pyroprocessing or advanced aqueous reprocessing involving partial decontamination and all operations associated with the processing and use of molten salt fuel, the investigations should include consideration of potential means to extract weapon-usable material through the misuse of normal plant equipment or through the introduction of additional systems that might be concealed from discovery (by the facility operator, the national control authority or by the IAEA).

6. Recognizing the importance of an ongoing consultative system with periodic feedback, and consistent with the provisions of applicable IAEA safeguards agreements, interactions with the agency should start during the Viability R&D phase. In the early stages of the Viability R&D phase, this effort would be intended to identify general aspects of the safeguards approach, alternative measures and any concept-specific R&D needed to facilitate later agreement on the technical measures to be applied.

   When sufficient information is available about a particular system, the interaction between the GIF proponents and the IAEA should lead to a case study by the Safeguards Department of the IAEA and the GIF proponents to consider each concept from the perspective of each of the five security areas. The case studies should be carried out under the provisions of the respective IAEA Member State Program of Technical Assistance to the IAEA safeguards. As appropriate for each of the five threats, specific consideration should be given to the shared use by the IAEA of operator measurement and monitoring systems as the primary means through which the IAEA would obtain verification data to meet its purposes, and to the authentication of the data provided to the IAEA to enable its use in forming credible and independent conclusions.

   During the Performance R&D phase, detailed aspects of the safeguards approach would be defined and specific equipment would be specified, developed (as required), procured, and tested. Overall quantification of the capabilities of the safeguards system would be carried out and improvements pursued as needed.

7. Using the safety analysis carried out for each prospective nuclear energy system, R&D should be carried out to identify the vulnerability to sabotage resulting in releases of radioactive material or theft resulting from breaches in containment, and any additional measures appropriate to counter such threats. Specifically, the safety analyses should be reviewed from the viewpoint of intentional acts as the initiators for the safety sequences identified, taking into account the use of force including armed attack and the consequent possibilities for the destruction of critical safety systems or structures, and the potential acts of knowledgeable insiders to operate the facility or systems in

an intentionally unsafe manner, or to disable or destroy critical safety systems, and combinations thereof.

8. R&D should be carried out on the reactor of each Generation IV system to determine how the reactor could be used for clandestine production of plutonium or ^{233}U, the impact of such use on the safe operation of the reactor, on enhancing the detectability of introducing fertile material into irradiation positions, and on enhancing the detectability of changes in the neutronic or thermohydraulic behavior of the reactor. Consideration should include the placement of fertile material within and near the reactor core, in amounts adequate to produce 8 kgs of Pu or ^{233}U per year. Consideration should be given to placing the fertile material in irradiation targets distinct from the fuel materials, or as additions to or replacements of normal fuel materials, as may be practical for a given concept.

   For each such possibility identified, the R&D should investigate means to minimize the vulnerability, e.g., through the introduction of structural features that would prevent the vulnerability from being exploited, or by increasing the hazards to the perpetrator of such an action, or by increasing the mass or bulk of material required to effect the vulnerability, or to increase the likelihood that steps taken by an adversary to exploit such a vulnerability would be detected promptly by the operator, the national control authority, and by the IAEA.

9. At each step in the fuel cycle and through the nuclear reactor, R&D should be carried out to define a concept for the knowledge base that will serve as the basis for determining the amounts, locations and characteristics of all material identified in #1 above at all times, in real time. This knowledge base would be the foundation for the material protection, control and accounting (MPC&A) system and would provide the foundation for the protective system employed by the facility operator. The MPC&A system would serve as the basis for the host country to determine the adequacy of the MPC&A system as one means through which the government of the host country would investigate any problems that might arise. The MPC&A system would also serve as the foundation of the "state system of accounting for and control of nuclear material (SSAC)" through which the IAEA would verify the findings of the state under safeguards agreements.

   The material knowledge base should include:

   a. Information generated through in-line and off-line instruments monitoring equipment (location, type, data, refresh rate)

   b. Information from sampling and laboratory measurements (frequency, analysis, precision and accuracy, time to results)

   c. Development and validation of inventory and flow predictive models for each operation and facility

   d. Information processing algorithms for the estimation of amounts and properties of all materials combining measurement, monitoring, analytical data and computer models for inventories and flow rates through process operations, including sequential estimates, and statistical uncertainties established through appropriate means

   e. Quality control provisions to ensure the completeness and accuracy of the knowledge generated.

5.4.2 Topic 2: Development of PR&PP Evaluation Criteria and Metrics

10. Taking into account the activities carried out in Subsection 5.4.1, R&D should be undertaken in parallel to produce the set of evaluation elements for the evaluation of intrinsic and extrinsic barriers separately addressing the five threats for the Viability and Performance Phases of Generation IV. Table 3 is intended to serve as a template for this process. A metric and an associated criterion should be developed that corresponds to each element for each threat for each phase.

5.4.3 Topic 3: Assessment Methodology

11. Deterring proliferation and nuclear terrorism will depend on the collective implementation of intrinsic and extrinsic measures that are intended to deter such acts by convincing potential perpetrators that attempts at proliferation would be detected and international responses would occur well before any success could be achieved, and that acts of nuclear terrorism are unlikely to either succeed or to avoid punishment. The selection and implementation of cost-effective combinations of such measures is complex, subtle, and involves many plausible alternatives. For this reason, efforts to-date to evaluate the risks of proliferation and nuclear terrorism against a system of intrinsic and extrinsic barriers have failed to provide clear and convincing answers. Explicit, comprehensive methods for evaluating the adequacy and requirements for a safeguards and physical protection system are needed to assess the protection and response capabilities it provides.

Research into the development of pragmatic assessment methodologies should be carried out, recognizing that the number of Generation IV systems that will be investigated will be limited (although the assessment methodology can be used in a wider range of applications, beyond the Generation IV initiative), that the development activities will involve in some cases collaboration of two or more countries and multiple institutions, and recognizing the related but distinct needs of facility operators, national control authorities and the IAEA. Such methodological research should reflect the needs of each potential user as a function of time, and differences in the information potentially available to each.

The process of developing this Proliferation Resistance and Physical Protection Assessment Methodology is likely to be iterative in nature, reflecting the complexity of the problem. Consideration should be given to the parallel development of this Proliferation Resistance and Physical Protection Assessment Methodology coupled to the efforts to be undertaken under topics I and II.

5.4.4 Conclusion

The R&D program established for Proliferation Resistance and Physical Protection should be designed in such a manner that the results provide an evolving framework for addressing the five threats, recognizing that detailed understanding will evolve as the system characteristics become increasingly well defined. In the Performance R&D phase of Generation IV, as the industrial partners begin to be involved in the development of specific nuclear energy systems, the nature of the interaction with the IAEA will evolve into increasingly specific systems with appropriate test and evaluation activities at key stages. Where relevant, prototype systems may themselves be subject to IAEA safeguards (this would be required in non-nuclear weapon States subject to comprehensive IAEA safeguards agreements, with routine safeguards required when nuclear material is involved).

Establishing a workable arrangement for minimizing access to information that will be of a sensitive nature will be essential for the success of the Viability and Performance phases of Generation IV. This will require effective arrangements to be followed within the GIF partners, and in some cases, the existing arrangements may have to be upgraded before information sharing between collaborating GIF parties can proceed. Similarly, provisions for each of the GIF partners to share sensitive information with the IAEA in relation to facility design information and inventory information already exists. The adequacy of the existing measures will need to be reconsidered in relation to the five security threats. The information provided to the IAEA for safeguards implementation and relating to the protection of nuclear materials (e.g., under the implementation of voluntary IPPAS missions) is limited to the minimum needed for the relevant goals to be met.

Appendix A

Criteria and Metrics for Viability and Performance Evaluations

Appendix A

Criteria and Metrics for Viability and Performance Evaluations

CRITERIA AND METRICS FOR SUSTAINABILITY GOAL 1

Goal Statement:

Sustainability-1 (SU1). Generation IV nuclear energy systems, including fuel cycles, will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production.

Evaluation for goal SU1 focuses on recognizing reactor/fuel cycle concepts that make sustainable demands upon the existing mineral resource base and ecosystems. The basic principle is that such concepts will have longer natural time scales of use and their disruptions of natural systems will be smaller for a given amount of energy production. Proposed metrics measure the satisfaction of these criteria by comparing to a reference concept, that of the LWR, the rate of resource consumption compared to the known resource base.

Summary table of criteria and metrics.

Criterion		Viability and Performance Evaluations
SU1-1	Fuel utilization	F = specific fuel resource consumption (MtU/GWyr)
SU1-2	Fuel cycle impact on environment	$M2 = ((H \text{ or } A)/R_{(H \text{ or } A)})_0/((H \text{ or } A)/R_{(H \text{ or } A)})_i$
SU1-3	Utilization of other resources	$M3 = [((m/R)_k)_0/((m/R)_k)_i]$

where

H or A = specific habitat or scenic area resource consumption for reactor/fuel cycle

$R_{(H \text{ or } A)}$ = total inventory of habitat or scenic area potentially affected by reactor/fuel cycle

R = total economically recoverable material resource inventory (Mt) used by the reactor/fuel cycle

m_k = annual consumption of the k-th type of rare material (e.g., helium)

i = system being evaluated

0 = reference system (ALWR).

Criteria Definitions

The justification for the forms of metrics suggested below is that each compares that of the reactor/fuel cycle of interest to that of the once-through ALWR.

SU1-1—Fuel Utilization

Definition: Generation IV systems will reduce the depletion of nuclear fuel resources.

Discussion: Assessment of the Sustainability Criterion 1 for a reactor/fuel cycle concept is concerned with its depletion of fuel. The basic principle is that Generation IV concepts will have longer natural time scales of use for a given amount of energy production. The attributes or factors to be considered in determining the degree to which a reactor/fuel cycle satisfies this criterion are its specific demands (consumption per unit of energy (either electrical or thermal produced from a reactor) for fuel compared to the economically accessible resource inventory of such fuel.

Proposed Metrics

Use of Fuel Resources

Viability and Performance Evaluation Metric: Quantitatively assess the use of fuel resources.

Systems that make better use of fuel, give longer natural time scales, and should be rated positively. This will include either achieving higher burn-ups, increased conversion ratios, or recycling of fuel material.

Metric: Specific fuel resource consumption: F = R/Qt

where

F	=	specific fuel resource consumption (Mt U/GWyr electric or equivalent product) for reactor/fuel cycle
R	=	total economically recoverable fuel resource inventory (Mt U) used by reactor/fuel cycle
Q	=	the total installed nuclear capacity (GW electric or equivalent)
t	=	natural time scale (yrs).

Uncertainty exists for what the specific values of F, R and Q will be in the time period that Generation IV systems will operate. The proposed scale is based on analysis performed by the Fuel Cycle Cross Cut Group:

- The center-right part of the scale on fuel utilization, expressed by low U feed per GWyr, covers the range of the specific fuel consumption required to achieve a natural time scale of 100 years (to the end of life of Generation IV systems deployed starting in 2030), for an intermediate value of projected deployment Q (average of 1,250–2,500 GWe from 2030–2100), for an intermediate projected value of economically recoverable uranium resources (8,500,000–15,000,000 Mt U).

- The right part of the scale is set at 10 times the midscale point, as representing a reasonable value for a fully sustainable fuel cycle. This does not result in a score that is directly proportional to the percent utilization of fuel resource. As utilization percentage grows, there is an economic ‘diminishing return’ on further efficiency (improving from 1–10% resource utilization is more valuable that improving from 90%–100%).

- In practical terms, the gains in fuel utilization achieved from higher thermal efficiency or limited Pu recycle will in general show values in the center of the scale. Certain combinations of these factors, and fuel cycles with multiple recycle of uranium, plutonium and/or thorium will show values corresponding to the middle of the right-hand side of the scale. Further effort toward nearly complete utilization of fuel and minor actinide consumption might produce specific fuel consumption in the rightmost part of the scale (and also contribute under SU2).

In addition, for final screening technical working groups should provide written discussion of the potential for symbiosis with other concepts that could affect the average fuel utilization of the entire Generation IV reactor fleet.

Use of fuel resources – viability and performance evaluation metric scale.

>300 Mt U feed/GWyr	250–300 Mt U feed/GWyr	200–250 Mt U feed/GWyr	150–200 Mt U feed/GWyr	100–150 Mt U feed/GWyr	10–100 Mt U feed/GWyr	<10 Mt U feed/GWyr

Analysis of uncertainties for recoverable resource inventory and total installed nuclear capacity will be included in the estimate of the use of fuel resources.

SU1-2—Fuel cycle impact on environment

Definition: Generation IV systems will reduce their impact on the environment.

Discussion: Assessment of the Sustainability Criterion 2 for a reactor/fuel cycle concept is concerned with the amount of environmental disruption associated with the fuel cycle. The basic principle is that Generation IV concepts will produce smaller disruption of natural systems for a given amount of energy production. The attributes to be considered in determining the degree to which a fuel cycle satisfies this criterion are its associated specific amount of environmental disruption (e.g., areas of habitat for affected species of biota) compared to the total inventory of such habitat, and the specific disruption of areas of scenic land enjoyed by humans for recreation or aesthetic enjoyment compared to the total inventory of such categories of land.

Proposed Metrics

Fuel Cycle Compatibility With the Environment

Viability and Performance Evaluations Metric: Quantitatively assess the use of specific habitat or scenic area compared to the ALWR once-through cycle.

Metric: Fuel cycle compatibility with environment: $M2 = ((H \text{ or } A)/R_{(H \text{ or } A)})_0/((H \text{ or } A)/R_{(H \text{ or } A)})_i$

where

(H or A) = specific habitat or scenic area resource consumption for reactor/fuel cycle of type or i respectively

$R_{(H \text{ or } A)}$ = total inventory of habitat or scenic area potentially affected by reactor/fuel cycle of type 0 or i, respectively.

Realistically it is unlikely that this metric will be able to discriminate between reactor/fuel cycles as most do not make serious demands upon sensitive environments.

SU1-3—Utilization of other resources

Definition: Generation IV systems will reduce the depletion of other specific resources.

Discussion: Assessment of Sustainability Criterion 3 for a reactor/fuel cycle concept is concerned with its depletion of identified specific material resources. Specific materials that need to be considered need to be identified among those used in a nuclear energy concept that are particularly scarce. The basic principle is that Generation IV concepts will have longer natural time scales of use for a given amount of energy production. The attributes or factors to be considered in determining the degree to which a reactor/fuel cycle satisfies this criterion are its specific demands (consumption per unit of energy (either electrical or thermal) produced from a reactor) for unique materials compared to the economically accessible resource inventory of the identified specific materials. Utilization of specific scarce resources applies to the whole energy system.

Proposed Metrics

Use of Other Specific Material Resources

Viability and Performance Evaluations Metric: Quantitatively assess the use of other identified specific resources compared to the ALWR once-through cycle.

Metric: Utilization of Other Resources: $M3 = [((m/R)_k)_0/((m/R)_k)_i]$

where

m_k = specific material resource consumption for reactor/fuel cycle of type 0 or i, respectively

R_k = total economically recoverable material resource inventory of type k used by reactor/fuel cycle of type 0 or i, respectively.

For most reactor/fuel cycles this metric will be unable to discriminate, as most do not demand scarce resources (e.g., Helium) under circumstances typical of the currently sized nuclear power economy. Should the scale of nuclear power employment become much greater than the current one this situation might change, but otherwise it is unlikely.

CRITERIA AND METRICS FOR SUSTAINABILITY GOAL 2

Goal Statement:

Sustainability-2 (SU2). Generation IV nuclear energy systems will minimize and manage their nuclear waste and notably reduce the long term stewardship burden in the future, thereby improving protection for the public health and the environment.

Evaluation of concepts with respect to SU-2 focuses on waste minimization, environmental impacts and stewardship burden for waste disposal. Waste minimization compares unit waste generation, decay heat production and long-lived hazard, as well as opportunities for optimization in waste management. While spent fuel and/or high-level wastes are a clear focus, all wastes should be considered. For environmental impacts, the broad range of emissions considered in a typical Environmental Impact Statement (EIS) is reviewed for unique concept features that provide advantages or disadvantages. Long-term stewardship burden, the length and intensity of societal responsibility, is a consequence of the wastes and environmental impacts. At the time of Viability Evaluation, knowledge is expected to be available to permit quantitative or semiquantitative assessment of most of these metrics. By Performance Evaluation, sufficient technical basis should exist to permit regulatory compliance assessment for all wastes and environmental impacts.

Summary table of criteria and metrics.

Criterion		Viability Evaluation	Performance Evaluation
SU2-1	Waste Minimization	Waste forms defined: • Mass: t/GWyr • Volume: m^3/GWyr • Long-term decay heat kW/GWyr • Long-term radiotoxicity/Gwyr	Same, but add: • Waste form performance • Repository design impact and performance assessment
SU2-2	Environmental impact of waste management and disposal	Sufficient information for Preliminary or Simplified Environmental Impact Analysis	Information for Environmental Impact Analysis

This results in five SU2 metrics for Viability Evaluation and further detail that may create additional metrics for Performance Evaluation. The relative importance of the metrics varies with national perspective and system concept priorities.

Criteria definitions

SU2-1—Waste minimization

Definition: Generation IV systems will offer the opportunity for minimization and improved management of all wastes compared to the ALWR once-through reference system.

Discussion: Considering that management of high-level radioactive waste (HLW) and/or spent nuclear fuel (SNF) is a major issue for current nuclear energy systems, it is expected that Generation IV system concepts will address these topics. Minimization of SNF/HLW per unit electric power produced is desirable, and Generation IV systems were evaluated for such potential in the earlier screening evaluations. At Viability Evaluation, systems should show the extent that they can meet these objectives, with indication of the level of confidence in such performance. The relative importance of these metrics may vary from nation to nation, as their SNL/HLW management approaches vary significantly. Because there is no single “quantity” measure to encompass all aspects of waste management that would be uniformly appropriate for the range of potential Generation IV concepts and the range of possible geologic repository settings, several metrics are considered.

The Viability and Performance Evaluations will include quantitative assessment of the adequacy a concept's waste management, based on metrics representing the amount and properties of HLW/SNF sent to final disposal. It is possible that systems will not have a complete basis for quantitative evaluation at the Viability Evaluation, with further R&D planned prior to the Performance Evaluation.

Proposed Metrics

Mass and Volume of HLW/SNF Sent to Final Disposal

Viability and Performance Evaluation Metric: HLW/SNF quantity per GWyr; Quantify mass and/or volume of HLW/SNF per GWyr): (MT/GWyr) and/or (m^3/GWyr)

Mass and volume are gross measures of waste quantity and capture some, but not all, of the difficulty in management/disposal of the waste. The absolute and relative importance of mass and volume depend on the waste form and disposal concept details (i.e., repository design). Mass is often used in reference to SNF. Mass and volume of HLW may be dependent on the waste forms selected and the matrix forming materials used to create the waste form, and the concentration of radionuclides achieved. Many advanced fuel cycles may vary substantially in mass, volume or both, per unit of generation. For example, higher burn-up may result in modest reduction in spent fuel per unit generation, while fuel recycle may result in greater reductions. Advanced fuel and waste forms offer a range of specific density so mass and volume may vary independently. At Viability Evaluation, systems should have well defined plans for management of SNF/HLW, including waste form descriptions and preliminary disposal evaluations, although in-depth waste form testing to support repository design and performance assessment may not be available until Performance Evaluation.

Mass of waste: metric scale.

>80 MT/GWeYr	40–80 MT/GweYr	20–40 MT/GWeYr	15–20 MT/GWeYr	10–15 MT/GWeYr	5–10 MT/GWeYr	<5 MT/GWeYr

Volume of waste: metric scale.

>100 m^3/GWeYr	50–100 m^3/GWeYr	20–50 m^3/GWeYr	15–20 m^3/GWeYr	10–15 m^3/GWeYr	5–10 m^3/GWeYr	<5 m^3/GWeYr

Decay Heat Thermal Output

Viability and Performance Evaluation Metric: Specific heat output in kW/GWyr in HLW/SNF sent to final disposal. The time variation of decay heat can have a significant impact on repository impacts so concepts may be scored separately at 50 and 500 years out of core to reflect operational and geologic post-closure times: (kW/GWyr)

In geologic disposal, management of decay heat can be a critical driver for repository design, capacity and performance. The long-term thermal output tends to dominate repository performance, while short-term thermal output is an operational issue, and less discriminating for sustainability of the concept. For some fuel cycles, the short-term versus long-term decay heat may be a discriminating feature, so decay heat as a function of time may be the desired metric for later evaluations. For example actinide recycle would result in equal short-term fission product heat, but far less longer-term actinide heat. For typical LWR spent fuel the fission products contribute 55% of decay heat at 50 years, but fission products drop to only 10% of total decay heat at 120 years and become negligible by 250 years. Thermal output during the operational period of repository disposal is a design and operations issue while thermal output during post-closure times may be a performance issue. Fuel cycles with partitioning of waste streams (reprocessing) may also offer options for optimization of disposal of wastes with differing thermal properties. At Viability Evaluation the waste characteristics should be sufficiently described to permit evaluation for disposal regulation, design, and performance impacts. By Performance Evaluation, the thermal aspects of the wastes should be demonstrated to be consistent with national waste management requirements.

Long Time (500 years out-of-core) Waste Decay Heat: scale.

>10 kW/GWeYr	5–10 kW/GWeYr	3–5 kW/GWeYr	1–3 kW/GWeYr	0.5–1 kW/GWeYr	0.1–0.5 kW/GWeYr	<0.1 kW/GWeYr

Radiotoxicity Measures

Viability and Performance Evaluation Metric: Long-lived radiotoxicity per GWyr compared to reference once-through fuel cycle.

The radioactivity of waste produced is another gross measure of waste production. But total activity produced per unit of fission energy does not vary greatly between nuclear systems, and activity is often not a major discriminator. However, some fuel cycles vary in the production and consumption of long-lived radionuclides sufficiently to affect the potential health hazard represented by the waste as measured by radiotoxicity. Such fuel cycle characteristics as high actinide consumption or actinide recycle resulting in less long-lived radiotoxicity. Radiotoxicity is a general measure of the potential hazard represented by the material, and can be measured in several ways. One simple representation of long-term toxicity is the sum of the specific activity of each radionuclide remaining 500 at years out-of-core multiplied by a biological dose factor such as the Sv/Bq factors from ICRP72, normalized per GWeYr. Major variations in this measure will be dominated by production and destruction of actinides because of the high dose conversion factors for alpha emitting isotopes.

How activity ultimately relates to repository dose is specific to the combination of waste form performance, repository design and the specific repository site. Viability Evaluation requires expectation that Generation IV wastes are consistent with disposal requirements. Depending on status of national repository programs, it may be possible to have complete performance assessment for Generation IV waste streams by Performance Evaluation.

Long-Lived (500 years out-of-core) Radiotoxicity MSv/GWeYr: metric scale.

>3,500 MSv/GWeYr	2,500–3,500 MSv/GWeYr	1,500–2,500 MSv/GWeYr	500–1,500 MSv/GWeYr	100–500 MSv/GWeYr	20–100 MSv/GWeYr	<20 MSv/GWeYr

SU2-2—Environmental Impact

Definition: Environmental and health impacts will be assessed relative to current nuclear systems. It is likely that many of these will not be discriminators for most Generation IV concepts. However, concepts may include unique features or processes that affect environmental issues.

Discussion: The environmental impacts of the complete reactor and associated fuel cycle must be considered. SU1 considers resource utilization, including land, minerals, etc., and SU2-1 considers high-level waste and spent fuel. This criterion considers all other wastes, emissions and operational environmental impacts. Concepts should identify unique features and processes with either beneficial or detrimental environmental implications. The typical list of potential impacts considered in an EIS provides a useful guide to the range of issues to consider. Viability Evaluation should include some level of preliminary or simplified environmental assessment. Performance Evaluation should include sufficient environmental assessment to allow commitment to a demonstration phase.

Proposed Metrics

Environmental Impacts

Viability and Performance Evaluation Metric: Qualitative ranking of the major positive and negative features of the environmental impact issues and unique characteristics of a concept: Scoring on environmental impact is likely to be nation specific.

This metric will measure the impact on the environment of a specific system as compared to alternative energy production choices. This includes the generating plant and the fuel cycle (including transportation, etc.) and any other facilities or operations needed to implement the concept. The following characteristics will be considered in the comparison with alternatives:

- **Construction of facilities:** Construction wastes, emissions and environmental disruption.
- **System operation:** Environmental impacts from both normal and off-normal operations including all waste categories (except HLW), worker and nonworker exposure, emissions, traffic, noise, visual impact, etc.
- **Decommissioning:** Facility decommissioning, decontamination, removal, and remediation processes, including exposures, emissions, wastes, etc.
- **Disposal:** low-level wastes, toxic and mixed wastes, nontoxic waste, etc.

Environmental Impact: metric scale.

Much worse than alternatives	Worse than alternatives	Similar to alternatives	Better than alternatives	Much better than alternatives

PROLIFERATION RESISTANCE AND PHYSICAL PROTECTION

NOTE: As indicated in Section 5 of the main report, it is a recommendation of the EMG that a methodology for assessing proliferation resistance and physical protection (PR&PP) needs to be developed. Identification of the appropriate criteria and the representative set of metrics for proliferation resistance and physical protection will be part of the methodology development. This section, therefore, provides some guidance and an approach to evaluating Generation IV systems for viability and performance with respect to PR&PP, but specific criteria and metrics are not listed.

Viability and Performance Evaluations in Relation to Security Concerns Arising in the Context of Generation IV

Goal Statement:

Proliferation Resistance and Physical Protection (PR&PP). Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and least desirable route for diversion or theft of weapons-usable materials and that they provide increased physical protection

Introduction

During the Screening for Potential that took place early in the Generation IV Technology Roadmap, the Goal and the screening concentrated on Proliferation Resistance, with focus on providing strong assurance that States or other groups will not choose Generation IV systems as sources for the diversion, undeclared production, or theft of nuclear materials.

In the Final Screening of the Generation IV Roadmap, the Technology Goal was clarified to envelope all security issues, captured under the label of Proliferation Resistance and Physical Protection. With regards to proliferation resistance, candidate nuclear energy systems were evaluated, inter alia, on the basis of measures that could minimize the possibility that a Generation IV nuclear energy system might contribute to proliferation. The evaluation focused on characteristics of fresh and spent fuel (radiation and other barriers) that increase the difficulty and time required to process materials obtained by diversion. In addition, consideration was given to physical protection provisions to address threats related to nuclear terrorism, with focus on assuring that Generation IV systems will be robustly resistant against potential attempts of theft and sabotage by terrorists and other non-State actors. The screening focused on characteristics of reactor safety systems that can simplify physical protection requirements to resist sabotage.

Recognizing that detailed system information is needed for a thorough evaluation, the proliferation resistance and physical protection screening was limited to three generalized criteria.

During the Roadmap screenings, the means available to counter threats of proliferation and terrorism were expressed as combinations of intrinsic and extrinsic barriers.

- *Intrinsic barriers* were defined in the final selection criteria in terms of material qualities (isotopic composition, chemical separability, mass and bulk, fuel matrix, radiation level, dilution and detectability characteristics), and by technical impediments that are inherent to a nuclear energy system such as facility unattractiveness and accessibility, mechanical impediments to material and vital equipment, and skill requirements.

- *Extrinsic barriers* were defined as including institutional controls, such as material control and accounting (MC&A) and physical protection performed by the nation-State to prevent theft and sabotage; the detection of diversion and misuse performed by international safeguards and the characteristics of the nuclear energy system intended to facilitate such safeguards; and by the specific undertakings accepted by a State under treaties, conventions, or agreements that the State is a party to.

Extrinsic barriers can compensate for intrinsic deficiencies. For example, a nuclear reactor, which might easily serve as a plutonium production reactor, could offer robust protection against undeclared plutonium production if that reactor were owned and operated not by the State importing the reactor but by the supplier, or if a multinational energy park was created with no opportunities for any State served by such a park to misoperate the reactor or to introduce fertile material into locations within or surrounding the core where plutonium (or ^{233}U) production might take place.

Shifting the Focus from Screening to Viability and Performance Evaluations

The GIF has now agreed upon the selection of six candidate concepts for future R&D consideration. Taking into account these selections, the emphasis in Generation IV will now shift from screening candidates to assuring that the candidates selected fulfill the relevant Generation IV goals and thus are suitable for future implementation.

In the Viability and Performance R&D phases of the Generation IV program, investigations should be carried out in the context of the potential vulnerability of each nuclear energy system in relation to the security issues defined below. The R&D program should be aimed at identifying, analyzing, developing, testing and evaluating alternative combinations of intrinsic and extrinsic barriers chosen for each nuclear energy system with the goal of providing a cost-effective approach to meeting the Generation IV goals.

To compete successfully, a nuclear energy system will have to be licensed by the competent national authorities, may require export or import permits,[1] may require approvals by regional control authorities,[2] and may be subject to safeguards by the International Atomic Energy Agency (IAEA). Prior to commercial deployment, these concerns will have to be addressed to the satisfaction of the responsible authorities. Their requirements will likely continue to evolve during the Viability and Performance R&D phases, further complicating this task. Moreover, R&D related to intrinsic barriers may require trade-offs to resolve conflicting aims.

The role of R&D in connection with proliferation resistance and physical protection should follow the following philosophy and priorities:

1. As first priority, design solutions should be sought that avoid or prevent vulnerabilities to external threats, and that mitigate the consequences of actions that cannot be prevented as a second priority

2. A defense-in-depth philosophy should be adopted as a means to assure that the protections required will be robust against all plausible threat scenarios[3]

1. Export licenses by competent national authorities are normally required for nuclear energy systems and nuclear materials. The Nuclear Suppliers Group and the Zangger Committee provide guidelines for such exports.

2. Nuclear facilities and nuclear material within the European Union require approvals from the Euratom organization, and in Argentina and Brazil require approval by the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials.

3. This in turn will require that design basis threats are specific enough to permit technical evaluations to be made.

3. A system of checks and balances should be included in the overall system concept to ensure that all systems addressing the specified threats are, and remain, effective.

While most of the R&D activities will be specific to the six Generation IV candidate systems, there is also a need to develop the infrastructure necessary for decision making during the Generation IV selection process, and to support the future needs of organizations entrusted with implementation and relevant control functions. Generation IV itself will not have a regulatory function per se; under the Viability and Performance R&D phases of Generation IV, R&D related to extrinsic barriers will in part be carried out in cooperation with the respective organizations, such that key issues are identified early on and are resolved over the period of each phase. Any significant impediments to licensing, export/import, financing, or IAEA safeguards as determined by the respective bodies will have a corresponding impact on support for a given candidate Generation IV nuclear energy system.

Security Issues Arising in Connection with Peaceful Nuclear Energy Applications

Five security areas or threats can be identified and classified into two broad areas in conjunction with the implementation of all nuclear energy systems. The mechanisms available for preventing such threats from becoming reality also differ.

Proliferation Resistance. Issues involving the proliferation of nuclear weapons:

1. *Nuclear weapons*. Misuse of a nuclear energy program undertaken for peaceful purposes by a State as part of a national program to acquire nuclear weapons. For proliferation, the State is the presumed actor; if such a nuclear weapons program were to be undertaken, it must be presumed that the State would use its full resources to organize and carry out the program while taking all means to avoid detection. This threat might be accomplished by diverting declared weapon-usable fissile material from a nuclear energy system, or by the undeclared production of weapon-usable fissile material within declared facilities, or through the clandestine replication of facilities or key equipment imported or developed indigenously for peaceful nuclear use. These acts are deterred by the risk of timely detection by international safeguards. The capabilities afforded by a given nuclear energy system and the associated deployment arrangements, together with the capabilities existing in the State at the time a nuclear energy system is introduced, determine the practical steps open to the State if it should attempt to acquire nuclear weapons. The more difficult it is to accomplish these steps, while avoiding early detection through the introduction of intrinsic and extrinsic barriers, the more proliferation resistant the nuclear energy system.

Physical Protection. Threats involving theft of materials suitable for nuclear explosives or radiation dispersal devices, or sabotage of facilities or transportation:

1. *Nuclear explosive devices*. Theft of weapon-usable fissile material for the production of one or more “nuclear explosive devices.” The weapon-usable fissile material might be stolen from a nuclear reactor, fuel cycle facility, or from an inter-facility shipment. The theft might involve an external attack on a facility or could involve one or a series of thefts by one or more “insiders.” The organization involved in the theft could be a national government, but would more likely be a terrorist organization or a criminal enterprise, or even individuals.

2. *Radiation dispersal devices (RDD)*. Theft of hazardous radioactive material for the construction of one or more RDD. Such RDDs might be produced from hazardous radioactive material obtained by theft from a nuclear reactor, reprocessing complex, transport vehicle, or a storage location or any other location where hazardous radioactive materials are encountered in the context of a nuclear

energy system. The theft might involve an external attack on a facility, or could involve one or a series of thefts by one or more “insiders.”

3. *Nuclear facility sabotage*: Sabotage of a nuclear facility with the intention of releasing radioactivity to harm the public, or of damaging the facility with resulting financial loss and loss of confidence in nuclear energy.[4] The sabotage could involve an armed attack upon a facility or crashing an aircraft into a facility. Alternatively, insiders acting alone could attempt to sabotage a reactor or engineered storage facility or reprocessing plant by operating the facility in an unsafe manner and/or by disabling critical plant safety systems.

4. *Nuclear transport sabotage.* Sabotage of transport systems carrying nuclear material or (especially) hazardous radioactive material arising in conjunction with the operation of a nuclear energy system, with the intention of releasing radioactivity to harm the public.[5] The sabotage might involve an armed attack upon a transport system, perhaps assisted by one or more insiders.

Addressing the Security Issues

Proliferation is unique, while the other four security issues are interrelated.

The potential use of peaceful nuclear energy programs to aid and conceal a clandestine nuclear weapons program was recognized even before there were nuclear power reactors. This concern has been addressed with remarkable, if not total, success through actions taken individually by concerned states and collectively under the international nonproliferation regime. In relation to the proliferation of nuclear weapons, the presumed actor would be the government of a sovereign state. The specific proliferation program undertaken by a State might focus on a part of the Generation IV nuclear energy system such as a fuel cycle facility, or even on particular equipment for uranium enrichment. Making Generation IV systems resistant to such misuse is a hedge against such possibilities. Such resistance would come primarily from a high probability of timely detection of diversion or undeclared production, by international safeguards. Systems will be more resistant to proliferation if all materials are unattractive for use in nuclear weapons, and would require substantial additional processing for such use, providing additional time for international reaction following the detection of diversion or undeclared production.

Intrinsic proliferation resistance barriers could include avoiding weapon-usable material in easily accessible forms, and material control and accounting integrated into all aspects of storage, processing, transport, use and waste management to facilitate a high probability of early detection of diversion. Extrinsic factors may have little to do with the specific characteristics, and more so with the commercial and intergovernmental arrangements under which such systems would be deployed. Extrinsic national, regional (as applicable) and IAEA safeguards may be facilitated by intrinsic provisions at the respective installations.

The other threats are normally considered in relation to possibilities for terrorist acts.[6] The sovereign responsibility of a State is to protect its citizens, assets, and institutions from terrorist acts. The

4. A reactor core and the spent fuel storage are of principal concern at a reactor, while at a reprocessing plant, the spent fuel storage, head-end cell, first separation stage, and high level liquid waste storage are of principal concern. At a waste conditioning facility, the feed solution of high active liquid waste, the vitrification process and the storage of vitrified canisters are of principal concern. At a waste repository, any spent fuel or vitrified waste containers are of concern.

5. Other potentially hazardous radioactive materials, e.g., intense isotopic sources used in industry and medicine are not considered in this paper.

6. It is conceivable that a state might stage attacks upon its own facilities as a means to conceal a proliferation program.

State must establish a legal framework for prohibiting such actions and restricting access to the facilities and materials exclusively for authorized purposes. The State must strive to be informed of threats before they are carried out, and establish the protective measures and response capabilities necessary to deny success. There are also international dimensions to terrorist threats; for example, the terrorists may be based outside the country where the attacks might take place, or the weapon-usable fissile material or highly-radioactive material might be taken from one country for use in another or might be taken during international transport. Surviving terrorists might seek safe haven in other countries following an attack.

Whereas international controls related to proliferation of nuclear weapons are well established and strongly supported by the international community, controls regarding terrorist threats have not reached this level of maturity and effectiveness. There are 12 international conventions in force today addressing terrorism, but they are not comprehensive and are not widely supported, and there are no verification steps to assure that the parties to those conventions adhere to their provisions. National legislation on physical protection also varies widely. There is an International Convention on Physical Protection of Nuclear Material (the CPPNM), the only international legal instrument in the area of physical protection that aims to avert potential dangers from the illegal acquisition and use of nuclear material. Efforts are currently underway to extend its reach from international shipments of nuclear material; however, the CPPNM provides for no inspection mechanism and is far from universal in adoption.

Intrinsic barriers against terrorist acts would include robust containment, passive safety systems that are difficult to disable or bypass, storage that is difficult to access, process systems that remove weapon-usable fissile material and hazardous radioactive materials from active areas to secure storage in case of threat. Most antiterrorist measures would be common to any nuclear installation, and most barriers would be extrinsic in nature and would likely be required in full measure regardless of the intrinsic barriers provided.

For non-State theft and sabotage, future consideration will be given to assuring that there is a close alignment between threat assessment methods and the safety assessment methods used for SR1, 2, and 3. The issues are similar—design basis accidents for safety analysis correspond to design basis threats for physical protection analysis. There exist well-developed approaches to vulnerability assessment for theft and sabotage, and the CPPNM and INFCIRC/225 provide useful guidelines. By evaluating non-State theft and sabotage separately from State diversion and undeclared production, these linkages can be used as the starting point for developing specific evaluation methods. Once such vulnerability assessments are completed, the performance of specific concepts can be assessed against the metrics to characterize a Generation IV nuclear energy system's robustness and costs.

Criteria for Viability and Performance Evaluations

During the Final Screening in the Generation IV Roadmap, recommendations for the criteria for Viability and Performance evaluations were indicated as follows:

- For proliferation resistance, life-cycle accessibility of weapon-usable material; safety implications and detectability of undeclared irradiation or enrichment; detectability of diversion; life-cycle costs of IAEA inspections, including provision of essential safeguards equipment, per GWyr

- For physical protection, life-cycle accessibility of weapon-usable material; life-cycle accessibility of hazardous radioactive material; robustness of facilities and transport systems against acts of sabotage instigated by insiders and/or external attacks by force or stealth; minimization of material control and accounting (MC&A) and physical protection costs per GWyr; transparency of the effectiveness of physical protection and MC&A measures and minimization of requirements for information control.

For each Generation IV system, the combination of intrinsic and extrinsic barriers proposed in relation to each of the five security issues will be evaluated against physical metrics and procedural clearances from the appropriate governmental agencies or intergovernmental organizations. The assessments will be made where possible using absolute scales, rather than by reference to a given system or fuel cycle concept. (The specific metrics and the combinatorial process to determine the overall suitability are being developed in a separate R&D program.)

Export strategies and international agreements will be considered when appropriate. During the Viability Assessment, feedback from relevant government agencies and the IAEA will be considered for specific potential increased or decreased risks.

Viability Evaluations

The comparative merits of each Generation IV nuclear energy system will be considered at appropriate points during the Viability phase of R&D. The findings will depend upon the evaluated resistance offered by each candidate system to generic risks of proliferation, theft and sabotage through combinations of the intrinsic and extrinsic barriers foreseen, the costs for securing that resistance and any security-related vulnerabilities that might make a specific concept untenable.

As indicated in the endpoints documentation for the Viability and Performance R&D phases (see Section 4 of this document), a preliminary safeguards and security strategy should be prepared during the Viability R&D phase. It should provide a coherent assessment of the five security areas and a conceptual approach defining the manner in which those areas would be addressed. Some parts of such a preliminary strategy would be of a confidential nature, and subject to the classification rules of the states involved. It may be necessary to establish arrangements between the U.S. and other Generation IV collaborating states, reflecting the sensitivity of the proliferation resistance/physical protection considerations, particularly as they relate to potential vulnerabilities and physical protection response mechanisms. Feedback on relevant parts of this strategy should be obtained from the appropriate governmental organizations within the host state, by regional control authorities and by the IAEA.

In the course of the Viability R&D, the sponsoring State and respective institutions involved in developing a Generation IV nuclear energy system should enter into a cooperative arrangement with the IAEA leading to an agreed conceptual safeguards approach and an action plan for its further development—for the reactor and all fuel cycle operations—as necessary to meet applicable national, regional and IAEA safeguards objectives and requirements as defined in IAEA publications INFCIRC/153 and INFCIRC/540.

The physical protection portion of the strategy should be based upon the examination of the nuclear energy system against design basis threats established for each of the five security concerns identified. The relevance of plant safety systems will be examined in relation to all threats involving theft or sabotage. During the Viability R&D phase, the provisions of the physical protection portion of the strategy should be discussed with the various authorities responsible for protection against terrorism and related threats within the state(s)[7] developing the nuclear energy system; and should meet or exceed the

7. The term "State(s)" indicates that the development process may involve collaboration by one or more States, in which case, all relevant requirements would apply to each State engaged in such collaboration.

standards in INFCIRC 225 and the provisions of the Convention on the Physical Protection of Nuclear Material.[8]

Viability Questions

To enable assessments to be made of the effective proliferation resistance and physical protection anticipated for a specific nuclear energy system, the Preliminary Safeguards and Security Strategy completed by the end of the Viability R&D phase should contain information sufficient to address the following questions. Note that this characterization will depend on the export arrangements anticipated. If more than one export package might be established, the following questions should be answered separately for each such export alternative.

1. Where and when will separated weapon-usable fissile material and hazardous radioactive materials be used or produced over the life cycle of the nuclear energy system?[9]

   Information provided on the reactor, fuel cycle facilities and transport systems concepts should be complete to the point that weapon-usable material and hazardous radioactive material arising over the projected life cycle of the nuclear energy system can be characterized over time and location:

   a. The types, amounts, and physical and chemical form(s) of all weapon-usable and hazardous radioactive materials likely to be encountered

   b. The physical containment of all weapon-usable and hazardous radioactive materials to be provided by containers, process cells and storage facility features

   c. The difficulty associated with producing separated weapon-usable fissile material from all material forms to be encountered and from all processes foreseen.

2. How will the measurement and monitoring information needed for national, regional and IAEA controls be provided? Specifically, what are the information sources, what provisions are foreseen for instrumentation and monitoring sensors? What sensors and information networks would be provided as part of the nuclear energy system to generate and collect such information? How would the information generated be authenticated by the user organizations so as to ensure that the sensors and information networks provide credible data?

3. Which information processing methods would be applied to provide positive control and current information on the location, amount, and status of all such material at all times? What steps would be taken to facilitate the use of this accounting and control information by the facility operator, state, regional authorities, and IAEA?

4. How and to what extent will intrinsic features of the nuclear energy system facilitate the implementation of effective and efficient extrinsic barriers, in particular safeguards to provide early detection diversion and undeclared production, to achieve proliferation resistance?

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8. In the United States, the authorities would include the Nuclear Regulatory Commission, but could also include the Department of Energy (if any reactors or fuel cycle operations would be carried out on DOE sites), and possibly the Department of Homeland Security.

9. As a matter of principle, the use of highly enriched uranium fuels should be avoided. Plutonium should not be separated fully from fission products; the level of radiation maintained should pose a lethal hazard as a means to deter theft and as a means to require additional process steps to enable the plutonium to be used in a nuclear weapon or nuclear explosive device.

5. How, and to what extent, will intrinsic features of the nuclear energy system, including the safety systems and relevant emergency response capabilities, enhance the physical protection of weapon-usable fissile material and hazardous radioactive material against acts of theft or sabotage? The anticipated performance of the physical protection system will be judged in relation to a set of design basis threats.

   R&D topics are provided in Section 5 of this document.

Performance Evaluations

Candidate Generation IV nuclear energy systems will be considered for support in the Performance R&D phase if, among other considerations, the findings of the Viability Evaluations are positive.

A Generation IV nuclear energy system will be evaluated again at the end of the Performance R&D phase to determine its suitability for prototype or demonstration development. As part of the Performance R&D phase, a safeguards and security strategy will have been prepared (see Endpoints for Viability and performance R&D phases, Section 4 of this document). The strategy document will provide sufficient information to determine that the following conditions have been met:

1. Competent international (IAEA), national, regional, and local authorities have:

   a. Reviewed and accepted the design basis threats for the five areas of concern, in accordance with national and international requirements, standards, or guidelines for each

   b. Assessed the effectiveness of the proposed strategy for addressing those threats, including the relevant concepts, systems, equipment and procedures, as supported by experimental confirmation, modeling, and computation

   c. Assessed the proposed safeguards implementation for all facilities that will process, store, examine or use nuclear material in the nuclear energy system.[10,11]

2. The business plan developed for commercial deployment within the state(s) developing the nuclear energy system, addresses the five concerns over the life-cycle foreseen for the nuclear energy system under the anticipated deployment arrangements in the states developing the nuclear energy system and under anticipated export arrangements;

3. The business plan for exports of the nuclear energy system, or any element thereof, addresses the:

   a. Criteria for determining the suitability of an importing state

   b. Analysis of alternative export options[12] and a review of proposed alternative export arrangements in relation to the guidelines promulgated by the Nuclear Suppliers Group and

10. IAEA safeguards are required on all nuclear materials and all nuclear facilities in non-nuclear weapon states parties to the Treaty for the Non-Proliferation of Nuclear Weapons (the NPT). All nuclear weapon-states (NWS) parties to the NPT have in force voluntary offer safeguards agreements with the IAEA. One of the reasons for applying IAEA safeguards in NWS is to gain experience in applying safeguards at advanced facilities that may be exported to non-nuclear weapon states. Note that when a future treaty banning the production of fissile material for use in nuclear weapons or other nuclear explosive devices, inspections at some or all peaceful nuclear installations in all states party to that treaty may be obligatory.

11. Under current provisions, equipment, staff and implementation costs are borne by IAEA member states according to a formula for mandatory assessments on member state treasuries. In some cases, states or facility operators are encouraged to include the equipment necessary for IAEA inspections, and to maintain that equipment as essential for plant operations.

the Zangger Committee, noting concerns in relation to dual-use technologies identified by the London Suppliers Group.

R&D topics are provided in Section 5 of this document.

Uncertainties Complicating Viability and Performance Assessments

Completing the steps needed for judging the adequacy of a given concept will be complicated and at times unpredictable. The advocates of a given concept will need to plan to devote attention to this subject, to remain in close contact with the parties that will influence decisions, and to attempt to provide the technical and procedural work necessary for success with incomplete guidance and few models to work from. The challenges will include the following, for example:

- All facilities that process, store, or transport materials in the nuclear energy system must be considered. But the contribution of the proliferation resistance and physical protection measures to total proliferation risk will depend on the institutional and political conditions in the State where the facility will be located. Those conditions can in turn vary with time and may be difficult to specify.

- The state of knowledge of the facility and material configuration and inventory, which depends on the effectiveness of verification procedures during construction and operation, and may be unknown or poorly specified for facilities handling materials late in their life cycles (e.g. repositories).

- The state of knowledge for methods to avoid or postpone detection and to more rapidly change material attractiveness. Existing knowledge in this area is not fully shared due to classification. Moreover, it may not be available to a given state, and in any case, will change with time.

- The relative weights to assign to near-term and to longer-term stages of a material's lifecycle, and the weighing of near-term and longer-term proliferation risks may be difficult to quantify.

- The uncertainty regarding terrorism, including whether the efforts today will lessen the threats tomorrow, or whether there might be a significant attack with its political, social and economic impacts. There also remains the sensitivity of examining these threats and the countermeasures, particularly when international collaboration is involved. Moreover, the steps to improve the legal framework concerning physical protection, even infrastructure-building, let alone operational activities, are hostage to the issues of national sovereignty and the concerns of sharing information that could weaken defensive arrangements.

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12. Including provisions intended to inhibit the spread of enrichment and reprocessing technology; all fresh fuel to be provided, all spent fuel to be delivered to a repository in an NWS; build-and-operate export arrangements; single state importer, indigenous fresh fuel manufacture using technology exported by the state(s) developing the nuclear energy system or using existing capabilities available to the importing state; or multiple state importer secured under a multinational energy park agreement.

CRITERIA AND METRICS FOR SAFETY AND RELIABILITY GOALS

General Comments for the Sections on the Safety and Reliability Goals

The Generation IV Roadmap "Technology Goals for Generation IV Nuclear Energy Systems" document introduces the safety and reliability goals in a way that provides an organizing principle to the full set of safety and reliability goals and criteria:

> *Safety and reliability are essential priorities in the development and operation of nuclear energy systems.* During normal operation or anticipated transients, nuclear energy systems must preserve their safety margins, prevent accidents, and keep accidents from deteriorating into more severe accidents. At the same time, competitiveness requires a very high level of reliability and performance.
>
> There has been a definite trend over the years to improve the safety and reliability of nuclear power plants, reduce the frequency and degree of offsite radioactive releases, and reduce the possibility of significant damage. Generation IV systems have goals to achieve the highest levels of safety and reliability and to better protect workers, public health, and the environment through further improvements. The three safety and reliability goals continue the past trend and are in accord with the regulatory policy to have designs that are safe and minimize the potential for severe accidents and their consequences.

It is important to recognize that the safety and reliability goals are in accord with the regulatory policy of all GIF partners. In particular, the following discussion draws upon the defense-in-depth policy of IAEA and a generalized view of risk that together provide the unifying logic for all the safety and reliability goals and their respective criteria.

The Generation IV goals related to safety and reliability seek a global and comprehensive improvement of the safety related architecture (i.e., engineered and passive safety systems, inherent characteristics, etc.). This underlying goal translates into a recommendation for the improvement of the entire defense-in-depth system.

In the framework of safety, the final objective is the reduction of the risk (frequency and consequences) linked to the installation under examination. The improvement in safety and reliability for Generation IV systems will be most transparent and convincing, when there is a reduction to all the accident categories/families, starting from the frequency of operational occurrences, including anticipated transients, and the probability of design extension conditions (former "beyond design basis") that include "severe plant conditions" (i.e., core melting.)

The approach for evaluating improvement in all three safety and reliability goals is based on a structured view of Defense in Depth implemented through Risk Management Techniques most amenable to the current state of facility design and operations definition (including operator credentials and training, operations/maintenance procedure development, and facility management policy development.)

The INSAG 10, "Defense in Depth in Nuclear Safety," document provides the following systematic view of how to achieve improvement in defense-in-depth:

5.1 Improvements in Defense in Depth

122. The approach for further improvement of defense-in-depth is similar for existing and for future plants. However, for future plants such improvements can be achieved in a more systematic and complete way. This includes:

- improving accident prevention, in particular by optimizing the balance between the measures taken at different levels of defense-in-depth and by increasing their independence;

- improving the confinement function.

124. Possible means for strengthening accident prevention are:

- increased thermal inertia;

- optimized human-machine interfaces;

- extended use of information technology;

- reduced complexity;

- improved maintainability;

- expanded use of passive features;

- more systematic consideration of the possibilities of multiple failures in the original plant design.

125. The confinement function for advanced reactors will be strengthened by approaches and initiatives consistent with the following systems:

- For advanced designs, it would be demonstrated, by deterministic and probabilistic means, that hypothetical severe accident sequences that could lead to large radioactive releases due to early containment failure are essentially eliminated with a high degree of confidence.

- Severe accidents that could lead to late containment failure would be considered explicitly in the design process for advanced reactors. This applies to both the prevention of such accidents and mitigation of their consequences, and includes a careful, realistic (best estimate) review of the confinement function and opportunities for improvement in such scenarios.

- For accident situations without core melt, it will need to be demonstrated for advanced designs that there is no necessity for protective measures (evacuation or sheltering) for people living in the vicinity of a plant. For those severe accidents that are considered explicitly in the design, it would be demonstrated by best estimate analysis that only protective measures that are very limited in scope in terms of both area and time would be needed (including restrictions in food consumption).

5.2 Levels of Defense in Depth for the Next Generation of Plants

126. Meeting the safety objectives set for the next generation of nuclear power plants will necessitate improving the strength and independence of the different levels of defense. The aim is to strengthen the preventive aspect and to consider explicitly the mitigation of the consequences of severe accidents consistent with the initiatives stated in Section 5.1. This development would include the following trends:

- Level 1, for the prevention of abnormal operation and failures is to be extended by considering in the basic design a larger set of operating conditions based on general operating experience and the results of safety studies. The aims would be to reduce the expected frequencies of initiating failures and to deal with all operating conditions, including full power, low power and all relevant shutdown conditions.

- Level 2, for the control of abnormal operation and the detection of failures, is to be reinforced (for example by more systematic use of limitation systems, independent from control systems), with feedback of operating experience, an improved human-machine interface and extended diagnostic systems. This covers instrumentation and control capabilities over the necessary ranges and the use of digital technology of proven reliability.

- Level 3, for the control of accidents within the design basis, is to consider a larger set of incident and accident conditions including, as appropriate, some conditions initiated by multiple failures, for which best estimate assumptions and data are used. Probabilistic studies and other analytical means will contribute to the definition of the incidents and accidents to be dealt with; special care needs to be given to reducing the likelihood of containment bypass sequences.

- Level 4, for the prevention of accident progression, is to consider systematically the wide range of preventive strategies for accident management and to include means to control accidents resulting in severe core damage. This will include suitable devices to protect the containment function such as the capability of the containment building to withstand hydrogen deflagration, or improved protection of the basemat for the prevention of melt-through.

- Level 5, for the mitigation of the radiological consequences of significant releases, could be reduced, owing to improvements at previous levels, and especially owing to reductions in source terms."

The following relationship between the Generation IV Goals and defense in depth can be suggested:

Suggested relationship between the Generation IV Goals and defense-in-depth.

Levels of Defense In Depth	Objective	Essential Means	Generation IV Goals
Level 1	Prevention of abnormal operation and failures	Conservative design and high quality in construction and operation	Safety and Reliability –1. Generation IV nuclear energy systems operations will excel in safety and reliability.
Level 2	Control of abnormal operation and detection of failures	Control, limiting and protection systems and other surveillance features	
Level 3	Control of accidents within the design basis	Engineered safety features and accident procedures	Safety and Reliability –2. Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.
Level 4	Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents	Complementary measures and accident management	Safety and Reliability–3. Generation IV nuclear energy systems will eliminate the need for offsite emergency response.
Level 5	Mitigation of radiological consequences of significant releases of radioactive materials	Offsite emergency response	

Risk management tools appropriate to the current level of development of detailed design and operations practice are to be applied to evaluate the need for alternative/complementary design options within each level of defense-in-depth. In this regard, risk management brings all the safety and reliability issues together. The approach for evaluating and controlling risk in Generation IV systems extends the popular view of probabilistic risk assessment (PRA) in several directions.

However, the detailed approaches for applying these ideas for the coming stages of Generation IV development—Viability Evaluation, Performance Evaluation, and later stages of commercialization—may require further R&D and will require further definition. The extension to the popular view of PRA begins with a general framework for analysis of risk in Figure 1. (To some, this is simply what PRA is, as described below; to others, it is a far cry from the set of event trees and fault trees they call PRA and a new name for the process could avoid unproductive argument.)

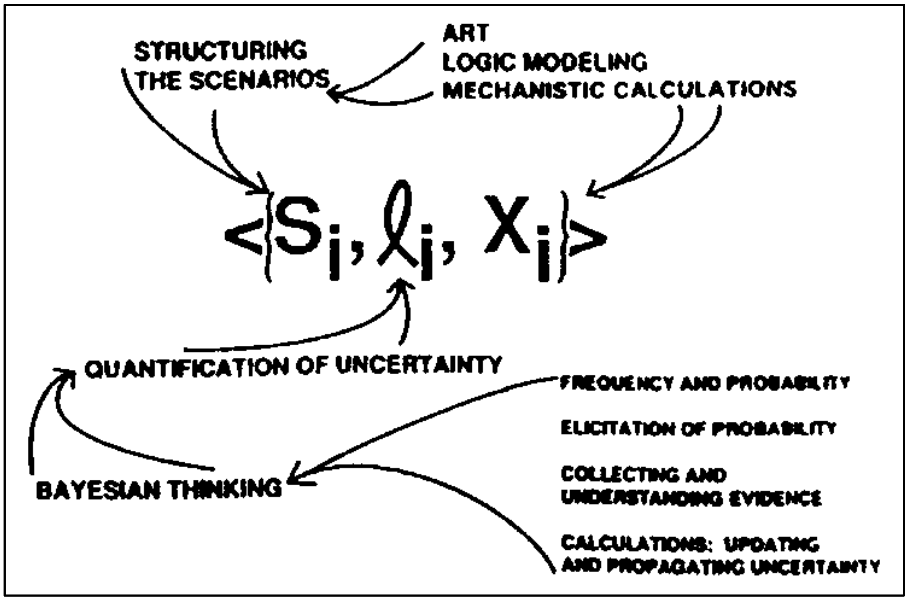

Figure 1. General Framework (Language) for Risk Analysis

Conceptually, risk analysis identifies a simple triplet:

S_i = the scenario (i.e., what can go wrong)

l_i = the likelihood of the scenarios occurring

X_i = the consequences of the complete scenario.

Then the risk analysis is the assembly of all possible such triplets. The art of risk analysis comes in structuring the search for scenarios, S_i, and in organizing the structure of the scenarios in a way that facilitates analysis and communication. This can mean effectiveness of search, ease of calculation, clarity of presentation, etc. The science comes in the detailed analysis of the identified scenarios and their consequences. And tying it all together is the structure for identifying, quantifying, and explaining the uncertainty in the elements of the analysis.

It is useful to recognize that at each level of defense-in-depth, PRA results provide an indication of the effectiveness of the defense-in-depth design/operations implementation. When these results are quantitative (i.e., uncertainty in the frequency of quantified consequences), criteria can be provided that define when additional defense-in-depth protection is required. When the results are qualitative, care is required to ensure that the integrated impacts of the results are considered and flexibility to respond to later quantitative results is retained.

It is important for the Generation IV Viability and Performance Evaluation phases to recognize that each of the elements of the triplet can be evaluated at alternative levels of detail. The following schema is one view of how such a step-wise progression of successive approximations to complete PRA detail could proceed. All cases fit the basic outline of Figure 1.

Case 1. Qualitative criteria such as the levels of defense-in-depth as discussed in INSAG 10, “Defense-in-Depth in Nuclear Safety and adopted in the Final Screening & R&D Prioritization criteria for the Generation IV Roadmap (e.g., robust engineered safety features and system models that have small and well-characterized uncertainty). Later cases become more analytical and quantitative, but the basic principles of these qualitative criteria continue to apply.

Case 2. Initiating event/potential consequence evaluation. In this case, analysts apply a formal search process to identify possible initiating events (departures from normal steady-state operations). The search must go further than replicating initiating events identified in Generation II and III PRAs or standard design practice. To be effective, it requires an understanding of the consequences to be modeled later in the full PRA. Maximum potential consequences are assigned in a conservative manner to lend some sense of priority to the list, but, lacking full event sequence development, cannot be taken literally. Such an examination provides the first input to later PRA development, often identifies potential new events, and thereby supplements the qualitative criteria of Case 1. A formal search process needs to be defined and tested, but will almost certainly borrow heavily from the hazard and operability (HAZOP) techniques of the chemical industry.

Case 3. Functional scenario development. One approach that has proved viable for a "first-look" PRA emphasizes a structured development of the detailed functional scenarios (the S_i of Figure 1) that can progress to damage states of interest. The design needs to have progressed to the point that the systems capable of providing key safety functions have been defined. Such scenarios can be developed in many forms (flow charts, narrative descriptions, event trees, etc., or the results of simulation). The important thing at this level is that they be complete as closely as possible to the scenarios that would be analyzed in a full quantitative PRA. Quantification of these scenarios may be crude at this time, but should allow for uncertainties due to random behavior and current state of knowledge. Major portions of a Case 3 PRA would depend on expert elicitation, bringing together the evidence (partially applicable data, experiential information, preliminary or complete calculations, etc; that is all available information. A similar approach is documented in a recent book published by AIChE [1].

Case 4. Full quantitative PRA. In PRA's most thorough application, the design must be far enough along to identify component characteristics, points of possible (not just planned) human interaction, procedures and training, physical mechanisms that apply (supported by mechanistic calculations and experiments (physics, chemistry, corrosion processes, etc.). Even when full data are not available, there must be enough information available to support expert elicitation [2]. Even in a "full quantitative PRA," there are alternative levels of available information to support quantification, e.g., success criteria and consequence results depend on the available detail in mechanistic calculations and experiments, on the available data, and on component performance in normal environments and highly stressed environments. Mechanistic calculations can run all the way from simple energy balances (these simple calculations can be useful to bracket a range of possible conditions that could occur in related scenarios) to the systematic consideration of uncertainty in the CSAU approach [3]. It is always necessary to apply judgment to such information and adapt what is available to what is needed; this transformation always results in uncertainty that needs to be considered in the analysis. The best form of the scenario structuring (event tree/fault tree models, simulation models, etc.), mechanistic analyses, and evaluation of likelihood (in Figure 1) will depend on the scenarios themselves, the state of design information, and the quality and applicability of available information. It will be useful to develop defined, alternative approaches to support the coming evaluations.

In the most common form of current PRA, the basic plant level scenarios (level 1 PRA) are structured by initiating events that couple to event tree sequences that, in turn, are analyzed by fault trees (logic models of system success/failure) and "first generation" human reliability methods (HRA). Core melt progression (level 2) scenarios are structured into event trees and post-release scenarios are structured by simulation models.

For Generation IV plants, with many passive systems, fault trees may be very simple when events proceed on expected trajectories. In such cases, it is possible that the use of "inherently safe" designs with primarily passive mitigation and protection systems will lead to very low probability of consequences using current analysis techniques. What may be needed is an improved search process for the scenarios, i.e., the risk may arise from unexpected ways the facility can end up operating outside its design assumptions. For example, ways the facility can end up operating outside its design assumptions could include scenarios such as:

- Where the human operators and maintenance personnel place the facility in unexpected conditions

- Where gradual degradation has led to unobserved corrosion or fatigue or other physical condition far from that envisioned in the design.

To address such issues, PRA must have an increased focus on human performance and on the human-machine interaction. This suggests that human factors and I&C/human-machine interface issues need to be addressed early on integral to the design process, rather than being additions after the physical design is fixed. New "second generation" human reliability analysis (HRA) methods can be used or adapted to the search process. They focus on context and control[4], on how the organization[5] and the plant state[6] can "set up" the operators for failure. This modern approach shifts the focus from human "error" as the cause of accidents to unsafe actions as a symptom of more systemic problems. The focus in both retrospective event investigation and in prospective HRA shifts to seeking understanding of why operators' actions were locally rational (how they can be locally rational), i.e., why what they did made sense at the time, given the context in which they were operating (as opposed to the hindsight of knowing how things turned out and how they might have progressed differently.)[4-7] The methods for a new type of HRA go beyond standard task analysis and table lookup of average human error probabilities. They look for the triggers for desirable and undesirable human performance.

SR References

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CRITERIA AND METRICS FOR SAFETY AND RELIABILITY GOAL 1

Goal Statement:

Safety and Reliability-1 (SR1). Generation IV nuclear energy systems operations will excel in safety and reliability.

Evaluation for goal SR1 focuses on safety and reliability during normal operation of all facilities in the nuclear energy system, from mining to the final disposal of waste. Thus the emphasis is on those high to medium probability events that set the forced outage rate, control routine worker safety, and result in routine emissions that could affect workers or the public. Assessment during Viability Evaluation is based on qualitative simplified PRA techniques, with quantitative estimates of the frequencies and consequences, where system design is sufficiently developed.

Goal SR1 considers facility attributes operable at the first two levels of defense-in-depth, as described above in the introduction to "Criteria and Metrics for Safety and Reliability Goals," that is, those features that can reduce the frequencies of initiating failures for all potential operating conditions and that can control abnormal operation and detect failures.

Summary table of criteria and metrics.

Criterion		Viability Evaluation	Performance Evaluation
SR1-1	Reliability	Search for PRA initiating events (causes of forced outages) and lines of defense	Forced outage rate probability distribution
SR1-2	Public and worker safety (routine exposures)	Search for initiating events and qualitative scenarios that could lead to unique routine exposure to radiation, chemical, and toxic hazards	Quantitative PRA for unique routine exposure to radiation, chemical, and toxic hazards
SR1-3	Public and worker safety (accidents)	Search for initiating events and qualitative scenarios that could lead to unique radiation, chemical, toxic, and handling hazards	Quantitative PRA for unique radiation, chemical, toxic, and handling hazards

Criteria Definitions

SR1-1—Reliability

Definition: Generation IV nuclear energy systems will excel in reliability.

Discussion: Plant reliability affects both safety and economics. The impact on economics occurs primarily through capacity factor and maintenance costs; it is discussed at the end of this section. The role of plant reliability in safety aligns with defense-in-depth Levels 1 and 2, prevention and control. Factors that lessen the chance of forced outage avoid the opportunity for accident sequences to develop. Forced outages can occur due to failures that directly preclude operation of the plant, and by failures that cause the plant to operate outside the limits set by its technical specifications. Low forced outage rates imply excellence in system design, maintenance, and operation, to prevent failure events of relatively high frequency from occurring, and from propagating to create conditions requiring plant shutdown. Under appropriate regulatory oversight, low forced outage rates also imply excellent performance in maintaining plant parameters and safety system availability and reliability inside the design safety limits specified by the plant technical specifications. High availability and reliability of safety systems reduces the probability that initiating events can lead to core damage.

The problem with emphasizing prevention in safety is that initiating events are not all created equal. The interactions among systems, given an initiating event and the impact of those interactions on plant thermal-hydraulic performance play a crucial role in identifying risk significant scenarios. Furthermore, attempting to identify major plant impact from simple metrics such as the number of safety systems, or from actual or hypothesized event descriptions, without plant-specific design details, as-built configuration, O&M practice, or plant-specific PRA is flawed. It ignores all the lessons we have learned in 25 years of doing plant-specific PRA. Risk impact is plant-specific and requires careful analysis. In well-designed facilities, risk comes primarily from unexpected interactions among systems and from internal,[13] external,[14] or combinations of events that defeat designed redundancy or expected systems responses. Another way of saying this is that risk does not come from combinations of best estimate or most likely conditions, but from less likely and more challenging situations. Therefore, a systematic, integrated examination of facility response against the safety criteria of interest, such as PRA, is needed, if the subtleties that affect risk are to be evaluated.

The impact of plant reliability on public safety is quantified under SR2, where PRA can calculate the frequency of plant states that can challenge the core and the plant. Identification of those states is an iterative part of the PRA, between mechanistic (thermal-hydraulic, neutronic, electrical, and mechanical) analysts and systems analysts. Mechanistic analyses are used to set success criteria on system functions, such that meeting those success criteria will ensure no serious challenge to the core or the plant. Note that the challenging plant states are generally a small subset of those that contribute to plant forced outages; they are the states that also partially disable mitigating systems (either unannounced failures of safety systems or conditions outside technical specifications). Thus, improving plant reliability for production may have little or no impact on safety unless the frequency of the challenging plant states is reduced (and reducing that frequency may have no discernible effect on availability, because the challenging states are often relatively minor contributors to shutdowns). However, if the frequencies of all contributors to forced outage rate are reduced (including those associated with challenging plant states), improvement in safety and reliability will result.

In the Viability Evaluation process, which occurs before the design is fully specified and well before operations and maintenance practices are established, it is not possible to make a meaningful calculation of forced outage rate. The uncertainties are so great that the results could not discriminate among systems. Nevertheless, unique features in design may offer early insight into the factors that could have major impact on forced outage rate. For example, redundancy in major secondary plant equipment such as main turbine generator or condenser, is minimal in Generation II and III plants to keep capital costs low. Consequently they have been significant contributors to downtime (forced and planned). So, unique features that offer improvements over Generation III plants can provide early indication of potential. Examples of such features that can affect forced outage rate and capacity factor (economics) would include:

- Enhanced redundancy and diversity (functional redundancy) that can improve both reliability and capacity factor.

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13 Relevant internal events could include operator errors, operation outside technical specifications, equipment failure, fire, flooding, missile generation, pipe whip, jet impact, or release of fluid from failed systems or from other installations on the site. Note that plants with fewer and simpler technical specifications would have less chance of such events.

14 Relevant external events could include earthquakes, floods, high winds, tornadoes, tsunami (tidal waves) and extreme meteorological conditions.

- Advanced control and monitoring systems that can reduce the cognitive challenges to operators, can improve forced outage rate and can minimize routine maintenance (improving capacity factor by eliminating the need for shutting down and opening equipment for inspection).

- Advanced control and monitoring systems that can flag oncoming failure thereby minimizing the chance of catastrophic failure (improving forced outage rate) and reducing repair time by replacing forced outages with planned outages (improving capacity factor).

- Design features that can improve average thermal efficiency over Generation II and III plants (fluctuations in efficiency introduce deratings [departures from 100% power]; reducing them can improve capacity factor).

- Design features that facilitate and simplify maintenance while optimizing the use of building space thereby reducing the chance of errors (improving forced outage rate) and making maintenance more efficient (improving capacity factor).

- Plant simplification offers the opportunity to improve reliability by reducing chances for failure and error; however, it can also reduce the opportunities for recovery.

- Safety system simplifications that reduce the number and complexity of technical specifications.|

Proposed Metrics

Plant Forced Outage Rate

Viability Evaluation Metric: Search for PRA initiating events (causes of forced outages) and lines of defense

Viability Evaluation shall use a Case 2 PRA approach (as described in the safety and reliability General Comments above), searching for initiating events. The set of events must be complete enough to support quantitative PRA in the Performance Evaluation. For each initiating event, identify the factors that could minimize the initiating event frequencies.

Unique features are especially important to identify, as they can permit discrimination among designs. Focus should be on design features and lines of defense, during all phases of operation. The following tables (Tables SR1-1 and SR1-2) list a number of features that should be considered when evaluating this criterion. A vulnerability leading to a higher forced outage rate calls for improvements in the number or quality of the lines of defense or an R&D program to reduce the vulnerability.

Each evaluation team must use its judgment to assess the likelihood that the unique factors affecting the system under evaluation improves or degrades the forced outage rate. Special attention shall be given to identification of human actions and human-machine interface issues that can impact forced outage rate. An effort should be made to characterize uncertainty in the effects of these characteristics and the R&D gaps that might resolve it. Successful closure of R&D gaps during the viability phase should lead to more narrow distributions.

Evaluation of the potential for high forced outage rate involves peer review of the completeness of the factors affecting forced outage rate and the likely effectiveness of potential improvements.

Table SR1-1. Design features to consider when evaluating plant forced outage rate.

Design Features Affecting Forced Outage Rate that Could Distinguish the System from Generation III	
• Frequency of initiating events • Experience with key components, materials, thermal cycling, corrosion, and aging • Scaling in size of components • Vulnerability to common cause failure • Ease of maintenance; low vulnerability to error • Load following capability • Accommodate loss of offsite power without reactor trip	• Sensitivity of operating plant to external events such as earthquakes, floods, and fires • Degree of use of advanced control systems; clarity of these systems to operators and cues to operators under various modes of system failure • Time for operators to take actions or intervene before the plant trips • Fewer or simpler technical specifications

Table SR1-2. Characteristics of lines of defense to consider when evaluating plant forced outage rate.

Characteristics of Lines of Defense that Could Distinguish the System from Generation III	
• For all systems, such as reactivity control, reactor heat removal, and power conversion, that can affect forced outages directly or by technical specifications • Redundancy and diversity • Flexibility to cover a wide range of conditions • Simplicity of configuration	• Degree of reliance on external power sources versus passive systems • Response of safety systems to external events such as earthquakes, floods, and fires • Time for operators to take actions or intervene before damage results • Optimized human-machine interfaces

Performance Evaluation Metric: Forced outage rate probability distribution

For the Performance Evaluation stage, the initiating events should be quantified to support quantitative PRA for SR2 and SR3 evaluation. SR1-Performance Evaluations will be based on the global level-of-defense architecture (the number and quality of implemented lines of defense) and on forced outage rate probability distributions for three categories of forced outages: (1) simple reactor trips, with no degradations in safety system capability; (2) shutdowns required by technical specifications (systems are degraded), but no demand for their automatic start has occurred; and (3) reactor trip in the presence of degraded mitigation systems.

All aspects of forced outage rate that are related to the design shall be considered. Performance Evaluation will be based on expert analysis, experiments and modeling of contributors to the plant forced outage rate.

Evaluations will also include screening for the possibility of unique routine exposure to radiation, chemical, and toxic hazards; and the possibility for unique radiation, chemical, toxic, and handling hazards. If unusual potential has been flagged in the screening steps, then a careful evaluation of the potential for exposure shall be made. These evaluations will support SR1-2 and SR1-3 Performance Evaluations. The construction and the operation of any nuclear installation must necessarily rely on a deep study clearly showing that the general safety requirements established by the safety authorities are met. In particular, it has to be shown that for all the plant operating conditions, both normal and off-normal, the risk, assessed in terms of dose to the personnel (inside the plant), dose to the population (outside the plant), and environment pollution is kept below the allowable limit.

Even at the Performance Evaluation stage there will be many uncertainties that could mask differences among the concepts. There will be no operating prototypes and there may be little operating experience with many aspects of the designs. A formulation for the forced outage rate is envisioned that can more clearly distinguish among the concepts:

$FOR(concept) = FOR_{COMMON} + FOR_{DESIGN\text{-}SPECIFIC}$

where

$FOR|_{COMMON}$ = the forced outage rate due to factors common to all concepts, including O&M management of the operating plant

$FOR|_{DESIGN\text{-}SPECIFIC}$ = The forced outage rate due to unique aspects of the concept under evaluation.

Then comparisons can be restricted to the fraction of the forced outage rate due to the $FOR|_{DESIGN\text{-}SPECIFIC}$ contribution. If such quantification is possible the following metric should be used:

Plant forced outage rate: metric scale.

Forced outage rate up to 5 per year and number or quality of lines of defense degraded	Forced outage rate up to 5 per year or number or quality of lines of defense degraded	Forced outage rate <1 per year, and lines of defense unchanged	Forced outage rate <1 per year and number or quality of lines of defense improved	Forced outage rate no higher than 0.2 per year, and number or quality of lines of defense improved

However, it is likely that even this level of quantitative analysis may not be possible at the Performance Evaluation stages. If so an alternative approach is planned. The list of significant factors from the Viability Evaluation should be refined by addressing the following considerations.

Design Considerations

The approach should follow NS-R-1: Safety of nuclear plant – Design:

“The plant design shall be such that its sensitivity to PIEs is minimized. The expected plant response to any plant initiating event shall be those of the following that can reasonably be achieved (in order of importance):

1. A plant initiating event produces no significant safety related effect or produces only a change in the plant towards a safe condition by inherent characteristics; or

2. Following a plant initiating event, the plant is rendered safe by passive safety features or by the action of safety systems that are continuously operating in the state necessary to control the plant initiating event; or

3. Following a plant initiating event, the plant is rendered safe by the action of safety systems that need to be brought into service in response to the plant initiating event; or

4. Following a plant initiating event, the plant is rendered safe by specified procedural actions."

Design/Operations Integrated Considerations

These evaluations will be based on a combination of expert assessment, experiments, and modeling to predict the effects of principal contributors to forced outage rate probability distributions.

Assume that plant management and operations practices will occur at average levels achieved by current plants, and focus on identifying all plant design characteristics that could cause the new plant forced outage rate to be different from that achieved in current nuclear plants. Because current nuclear plants already achieve a commendably low average forced-outage rate, a particular focus during evaluation will be placed on identifying plant design characteristics with the potential to substantially degrade forced-outage performance relative to current plants. Because of the anticipated design quality, special emphasis on human factors is essential, as discussed above in the safety and reliability general comments.

For each identified design characteristic, a systematic assessment will be performed to predict how the characteristic would contribute to increasing or reducing the plant forced outage rate, using a combination of experimental data and modeling, and a detailed assessment of the uncertainty in the predicted contribution will also be performed. A systematic weighting of all the contributors will then be used to predict the potential forced outage rates of the proposed plant design, relative to the rate obtained in current plants. A sensitivity study will then be used to quantify the uncertainty in the predicted relative forced outage rate, and to identify the largest sources of the uncertainty. For the viability evaluation, the R&D needed to reduce the primary sources of uncertainty will also be identified and listed. For both the viability and performance evaluations comparisons between concepts will be based on a balance between potential (the upper 75th percentile confidence level for relative forced outage rate) versus risk (standard deviation of the relative forced outage rate).

Safety related architecture assessment. The safety related architecture should also be assessed using the lines of defense (LOD) method that aims to assess the plant safety through the identification and quantification of all the lines of defense implemented to prevent, manage and mitigate the accident consequences. Such a method does not replace those currently used in the studies of reactor safety (Failure Mode and Effects Analysis, Initiator Events identification and grouping, Event Trees construction and evaluation, PRA) but, on the contrary, aims in providing to the designers' team a set of complementary and additional information the other methods often do not highlight in a clear and sufficient way.

The generality of the method allows its application essentially regardless of the plant detailed layout and design; also, it does not require detailed information about the plant systems and components. Therefore it appears to be particularly suitable for the studies concerning the safety of nuclear devices for which, generally speaking, only a very preliminary design is outlined.

Applied during the design process or for the assessment of an already defined safety related architecture, this methodology aims to easily assess the global plant safety level through the identification and the quantification of all the lines of defense already implemented to prevent, manage, and mitigate the accident consequences. Such an approach reaches design recommendations as output for complementary LOD implementation or for motivated LOD suppression. It produces information directly concerning the LOD characteristics especially in terms of requested reliability. This is essential for an optimized system/component classification.

Thus, it appears to be particularly suitable for the preliminary safety assessment associated with first phases of plant design, as well as in assessing future reactors and innovative concepts which architecture is already defined.

In this case, Performance Evaluation involves detailed peer review. At this stage, the design should be sufficiently complete and R&D gaps sufficiently resolved to allow some detailed calculations and to support judgments by reference to experiments and analyses. The basis for the judgments represented in the qualitative analysis should be reviewed for completeness and quality and for the qualitative and quantitative descriptions of uncertainty.

SR1-2—Worker and Public Safety and Routine Exposures

Definition: Generation IV nuclear energy systems will excel in safety and will not expose workers and the public to significant risk via routine exposure to radiation or hazardous material.

Discussion: Given the premise of high quality design, monitoring, and operation, routine exposure should be minimal. This is true in most well designed and managed industrial facilities, including nuclear facilities, today. It is important to identify unique hazards. However, risk is a matter of hazards and safeguards. Generally, routine exposure is a consequence of poor management and practices, rather than inherent in design concept. Nevertheless, evaluators must be alert to special aspects of each system. The role of routine exposure in safety aligns with defense-in-depth Levels 1 and 2, prevention and control.

Even if worker safety is protected, a unique hazard could cause additional maintenance cost associated with time delays and staff hours associated with controlling unusual hazards. While that is not a reliability issue, it will be most efficient to identify such potential costs during this evaluation.

Proposed Metrics

Routine Exposure to Radiation or Hazardous Materials

Viability Evaluation Metric: Search for initiating events and qualitative scenarios that could lead to unique routine exposure to radiation, chemical, and toxic hazards.

Evaluators must be alert to unusual potential for routine exposure from each system. Possible hazards would include coolant compatibility with humans and environment. Evaluators must also separate design issues from management issues. Designs that avoid or minimize management control can be advantageous. A Case 3 simplified PRA (initiating events and qualitative scenario descriptions) should be developed for unique hazards. An essential part of the evaluation is a peer review process that examines the simplified PRA for completeness, thorough treatment of human factors, and identification of relevant R&D gaps (uncertainty) affecting risk.

Performance Evaluation Metric: Quantitative PRA for unique routine exposure to radiation, chemical, and toxic hazards.

A Case 4 quantitative PRA shall be completed for unique routine exposure scenarios developed during the Viability Evaluation. The probability distribution of exposure consequences is the result. Again peer review of the analysis and especially the judgments is the basis of the evaluation.

SR1-3—Worker/Public Safety Accidents

Definition: Generation IV nuclear energy systems will excel in safety and will not expose workers to significant accident hazard, involving radiation, hazardous materials, or severe physical conditions. Radiological releases from major plant accidents is the subject of Safety and Reliability 2 and 3.

Discussion: As in routine exposure, personnel accidents are more often a function of company management and culture than inherent to the design. Still, it is clear that the hazard presented by one facility may be greater than that presented by another. When that is true, evaluators must examine the protection against that hazard—the safeguards—to see if risk is balanced by such measures. So the first step is to identify any unique hazards, those not present in other facilities. The hazards may be radioactive, chemically active, toxic, or physical such as high temperature or pressure. Note that the role of plant reliability in safety aligns with defense-in-depth Level 3—control of accidents within the design basis. While it could, therefore, align better with SR2, it is retained under SR1 because it follows similar evaluation steps with other SR1 criteria.

When hazard-screening analysis identifies unique hazards, evaluators must follow up with safeguards-screening to ensure workers and the public are protected at a level commensurate with the potential for harm. In significant cases, calculation of the risks, probabilities, and consequences can provide an assessment of the risk. As in other criteria, both intrinsic and extrinsic protection is possible. Intrinsic (designed in) protection can be more convincing to observers and may be more reliable.

Proposed Metrics

Accidental Exposure to Radiation, Hazardous Materials, or Physical Conditions

Viability Evaluation Metric: Search for initiating events and qualitative scenarios that could lead to unique radiation, chemical, toxic, and handling hazards.

Evaluators must be alert to unusual potential for accidental exposure to radiation. A Case 3 simplified PRA (initiating events and qualitative scenario descriptions) should be developed for unique hazards. An essential part of the evaluation is a peer review process that examines the simplified PRA for completeness, thorough treatment of human factors, and identification of relevant R&D gaps (uncertainty) affecting risk.

Performance Evaluation Metric: Quantitative PRA for unique radiation, chemical, toxic, and handling hazards.

A Case 4 quantitative PRA shall be completed for unique routine exposure scenarios developed during the Viability Evaluation. The probability distribution of exposure consequences is the result. Again peer review of the analysis and especially the judgments is the basis of the evaluation.

CRITERIA AND METRICS FOR SAFETY AND RELIABILITY GOAL 2

Goal Statement:

Safety and Reliability-2 (SR2). Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.

Evaluation for goal SR2 identifies facility attributes that, using models and experiments, create high confidence that all identified accident sequences are correctly managed and that reactor core damage will have a very low likelihood or can be excluded or practically excluded by design (and in other facilities, that the release of radioactive material from its most immediate confinement or nuclear criticality can not occur.) For performance evaluations much of the information required for a Preliminary Safety Analysis Report will be available, so the likelihood of core (or other facility) damage can be evaluated quantitatively for specific design extension conditions.

For Viability evaluation, a Case 3 simplified PRA (see safety and reliability General Comments above), should be completed, identifying potential initiating events and analyzing a representative subset of the ensuing accident scenarios, including identification and ranking of phenomena that govern the accident sequence transients, assessment of the capability of codes to model the dominant phenomena, identification of separate effects and integral experiments required for code validation, and modeling of a subset of the sequences to demonstrate the estimation of uncertainty. For performance evaluation, a Case 4 quantitative PRA is needed. Results can be presented as a frequency probability distribution which reflects all sources of uncertainty in models and experiments. For design information available at viability evaluation, an approximate analysis of the safety related architecture using the lines of defense (LOD) analysis, as described above in the introduction to "Criteria and Metrics for Safety and Reliability Goals," can identify conflicts with safety fundamentals.

As part of the simplified and quantitative PRAs, analysts should identify major design characteristics that are likely to robustly bound potential transient power, temperature, chemical reaction, and mechanical stresses well inside damage thresholds. Equally important, the screening credits design approaches that facilitate the modeling and experiments required to predict quantitatively the uncertainty of safety margins.

Summary table of criteria and metrics.

<table>
<tr><th colspan="2">Criterion</th><th>Viability Evaluation</th><th>Performance Evaluations</th></tr>
<tr><td>SR2-1</td><td>Robust engineered safety features</td><td rowspan="2">Search for initiating events and qualitative scenarios, combined with number/ quality of lines of defense

Robust engineered safety features are mapped in the scenarios; factors affecting uncertainty are identified</td><td rowspan="2">Probability distribution for core damage frequency (or release from normal configuration for nonreactor facilities), combined with number/quality of lines of defense</td></tr>
<tr><td>SR2-2</td><td>System models have small and well-characterized uncertainty (physical models/well-scaled experiments)</td></tr>
</table>

Criteria Definitions

SR2-1—Robust engineered safety features

Definition: Generation IV facilities will have engineered safety features and/or inherent features (for reactors: power control, heat removal, and radionuclide confinement) that will transparently bound the accessible range of operating and accident conditions and will allow the margins in safety-related system parameters (fuel temperature, containment pressure, etc.) to be predicted with very low uncertainty, inside this range of conditions.

Discussion: To provide high confidence that damage is precluded or has very small probability for all the plausible plant conditions (design-basis accidents and design extension conditions [see the introduction to the SR Goals above]), the accessible range of facility operating and accident conditions must be bounded by inherent design characteristics and by simplicity of the technical specifications that guide facility operation. Inside these boundaries the performance and reliability of safety related design features depends on the application of the following excellent design practice:

- Redundancy
- Prevention of common mode failure due to internal or external hazards, by physical or spatial separation and structural protection
- Prevention of common mode failure due to design, manufacturing, construction, commissioning, maintenance or other human intervention, by diversity or functional redundancy
- Automation to reduce vulnerability to human failure, at least in the initial phase of an incident or an accident
- Testability to provide clear evidence of system availability and performance
- Qualification of systems, components and structures for specific environmental conditions that may result from an accident or an external hazard.

Some of these design features can be introduced during detailed design; others are inherent to fundamental characteristics of systems. The evaluations give credit to those fundamental features that are likely to support high confidence and transparency in predictions of low core damage probability. For reactors, simple (often passive) reactivity control, heat removal, and radionuclide confinement methods reduce the complexity of system interactions and require less intensive surveillance to confirm operability. Robust fuel and core designs with long thermal time constants maintain more predictable geometry and thermophysical properties over the full range of accessible plant states.

Proposed Evaluation

Principal Safety System Function

Viability Evaluation: Review for completeness of the design of the systems that perform the principal safety system function.

Under SR2-1, the first portion of the evaluation involves peer review of the completeness of the design of the systems that perform the principal safety functions (reliable reactivity control and decay heat removal for reactors). Detailed transient analysis for a subset of these design transients, selected from those identified in SR1 to challenge each of the primary safety functions, are reviewed to determine the magnitude and uncertainty of margins in major safety parameters. Where design gaps exist, reasonable assumptions can be made for the potential system performance, and an explanation for how the gap will be removed by Performance R&D provided. The magnitude of the safety margins predicted for these selected transients, and their uncertainties, will be compared qualitatively to the reference Generation III system to determine whether they provide an improvement in the performance of the key safety functions (both in the magnitude, and uncertainty, of the margins).

More specific requirements, beyond the qualitative assessment called for here, may be developed as a part of risk and safety crosscut research performed during the Viability Evaluation phase.

Performance Evaluation: Detailed peer review completeness of the design of the systems that perform the principal safety system function.

SR2-1 Performance Evaluation involves a detailed peer review for the level of completeness of design of the systems which perform the principal safety functions. At this stage, the system design should be sufficiently complete to allow detailed transient analysis across the full range of potential initiating events identified in SR1. These transient analyses will be reviewed for completeness and quality, and the magnitude and uncertainty in the margins in the major safety-related parameters quantified as probability distributions. Comparison of the resulting probability distribution for core damage frequency will be made with the reference Generation III system.

SR2-2—System models have small and well-characterized uncertainties

Definition: Generation IV systems will be governed by dominant phenomena and phenomena interactions that can be predicted with very high and well-bounded certainty using models and experiments.

Discussion: Accident sequence analysis and calculation of damage-frequency probability distributions requires physically based models with uncertainties that have been accurately characterized by comparison with separate effects and integral experimental data. This screening criterion identifies system attributes that are likely to reduce modeling uncertainty. Some phenomena such as conduction and single-phase convective heat transfer in channels, can be predicted with low uncertainty using appropriate data from well-designed and instrumented separate effects experiments. Other phenomena, such as critical heat flux and strongly multidimensional flows, are more complex and introduce greater uncertainty in modeling. Well-scaled integral experiments are required to confirm the completeness and accuracy of integral models.

Proposed Evaluation

Transient Models

Viability Evaluation: Review quality and completeness of the models used in system transient response predictions.

SR2-2 Viability Evaluation provides peer review of the quality and completeness of the transient models used to predict the system transient response to initiating events identified in SR2-1 and SR1, and to accurately quantify the uncertainty in these predictions through the application of uncertainty assessment methods such as the Code Scaling, Applicability, and Uncertainty (CSAU) method.[1] The major elements of the evaluation will include peer review of the phenomena identification and ranking that has been performed for the selected transients. The review will confirm that all dominant phenomena can be well characterized through physically based models, and that adequately scaled separate effects experiments exist, or will be performed during Performance R&D, to validate models used for all dominant phenomena. This review will include a detailed consideration of whether the separate effects experiments can adequately reproduce the range of boundary and initial conditions that would exist in the prototypical system. The capability of the transient analysis codes to predict the integral response of the system will also be assessed, including an assessment of the quality of the scaling and design of existing or proposed integral experiments to validate the integral predictive capability of the codes.

The primary output of the SR2-2 Viability Evaluation will be a review of the adequacy of proposed experimental and code development work, and an assessment of how well uncertainty in system transient response can be characterized, compared to the transient modeling for the reference Generation III system.

Performance Evaluation: Detailed peer review to verify that experimental and code development work proposed at the time of Viability Evaluation has been successful.

SR2-2 Performance evaluation provides detailed peer review to verify that experimental and code development work proposed at the time of Viability Evaluation has been successful. The review examines the same issues as the SR2-2 Viability Evaluation, but for the full range of initiating events identified in SR1 analysis. The most important aspect of the SR2-2 Performance Evaluation is the confirmatory effort to verify that the system designers have systematically identified and quantified, or bounded, all sources of uncertainty in predicting the system transient response to initiating events.

SR2 References

1. B. E. Boyack et al., “An Overview of the Code Scaling, Applicability, and Uncertainty Evaluation Methodology,” *Nuclear Engineering and Design*, Vol. 119, pp. 1–16, 1990.

CRITERIA AND METRICS FOR SAFETY AND RELIABILITY GOAL 3

Goal Statement:

Safety and Reliability-3 (SR3). Generation IV nuclear energy systems will eliminate the need for offsite emergency response.

Evaluation for goal SR3 considers system attributes that allow demonstration, with high confidence that the radioactive release from any scenario results in doses that are insignificant for public health consequences. Such confidence must come from the knowledge that reactor core damage (design extension conditions as described in the above introduction to “Criteria and Metrics for Safety and Reliability Goals”) has very low probability (SR1 and 2) and that mitigation features provide additional lines of defense to account for any significant residual risk. This confidence comes from three sources: accurate bounding prediction of the timing and magnitude of radioactive source terms and energy releases; accurate assessment of the effectiveness of the confinement system in accommodating the all bounding energy releases and providing holdup of radioactive material; and assessment of the resulting offsite dose probability distribution and comparison against appropriate standards for individual and societal risk. Viability assessment considers how well severe-accident phenomena can be characterized and modeled for the system based on the scenarios identified in the simplified PRA. Criteria SR3-1 and SR3-2 apply for viability assessment (Case 3 PRA). For performance evaluations, quantitative evaluation of damage, release and transport, and comparison of resulting dose relative to public health criteria, are used. Criteria SR3-3 and SR3-4 are used for performance assessment (Case 4 PRA).

Summary table of criteria and metrics.

Criterion		Viability Evaluation	Performance Evaluation
SR3-1	Radioactive source/energy release magnitude and timing understood and bounded by inherent features	Source term probability distribution	Included in SR3-3 and SR3-4 evaluations
SR3-2	Confinement or containment provides robust mitigation of bounding source and energy releases	Offsite dose probability distribution	
SR3-3	No additional individual risk	NA	Quantitative – from PRA results
SR3-4	Societal risk comparable to competing technology	NA	Quantitative – from PRA results

Criteria definitions

SR3-1—Radioactive source/energy release magnitude and timing understood and bounded by inherent features

Definition: In Generation IV systems, the potential timing and magnitude of the release of radioactive material from the core, and energy from all potential internal and external sources will be understood, minimized, and bounded by inherent features of the fuel and confinement structures, including thermal inertia and chemical stability.

Discussion: The principle of defense-in-depth, as discussed in the introduction to SR goals, requires that Generation IV reactor systems include independent confinement or containment systems that can provide sufficient hold-up of radioactive materials to meet offsite dose goals, for the physically possible timing and magnitude of releases of radioactive material. This independent confinement or containment system must be designed to function appropriately when subjected to the full range of physically plausible energy source magnitudes and timing that could be derived from internal or external sources.

- *Excellent fuel damage resistance.* Those fission products which are gases, or become vapors at high temperatures, can be mobilized by fuel damage at elevated temperatures. Highly robust fuel forms can delay and reduce fission product releases after fuel is damaged by high temperatures and/or oxidation, and can prevent the propagation of failure to neighboring fuel material. These fuel features can delay the release and reduce the fraction of the fission products that can be mobilized. Thus, these features mitigate the effects of reaching the conditions for fuel damage in the *Excellent Fuel Damage Resistance and Well Bounded, Understood, and Limited Number of Mechanisms for Significant Energy Releases* metric below.

- *Bounded and controllable energy releases.* The confinement/containment structures can be subjected to a range of energy releases with the potential to damage the structures' capability to hold up radioactive materials. Systems are preferred where the timing and magnitude for potential release of all internal stored energy sources, and external energy sources, can be predicted and bounded with high confidence.

- *Predictability of source term/energy release.* Systems are preferred where detailed, mechanistic models can accurately predict time-dependent probability distributions for the fractional release and physical and chemical form of radionuclides released from fuel subjected to overheating and/or oxidation damage (or for damage to the most immediate confinement or criticality for nonreactor facilities), and predict the timing and magnitude of all energy releases that could damage confinement and containment structures. These factors also affect the metric. For reactors, these models will be based on phenomenological models for structural and fuel damage and for fission product transport to the reactor coolant system, for a spectrum of accident sequences. These models will be validated against well scaled and instrumented experiments.

Proposed Evaluation

Excellent Fuel Damage Resistance and Well Bounded, Understood, and Limited Number of Mechanisms for Significant Energy Releases

Viability Evaluation: Fuel damage resistance and energy release mechanisms assessment.

Fuel damage resistance and energy release mechanisms will be assessed using the results of fuel performance tests compared to the predicted conditions resulting from the scenarios identified in the simplified PRA and energy release mechanisms will be identified by the simplified PRA. Particular attention will be given to assessing the degree of understanding of those mechanisms from the conceptual system design performance and the ability to calculate the system response with reasonable uncertainty.

A Case 3 simplified PRA (qualitative scenario descriptions) will describe how scenarios could lead to significant releases, even at very low frequency. Because Generation IV designs may use "inherently safe" designs with primarily passive mitigation and protection systems, very low probability of consequences are anticipated. What may be needed is an improved search process for the scenarios (the risk may arise from unexpected ways the facility can end up operating outside its design assumptions).

For example, ways the facility can end up operating outside its design assumptions could include scenarios involving human operators and maintenance personnel placing the facility in unexpected conditions or situations where gradual degradation has led to unobserved corrosion or fatigue or other physical condition far from that envisioned in the design.

For the design-extension scenarios identified, the SR3-1 Viability Evaluation will assess the level of understanding of the system source term, and the ability to predict and bound the magnitude and timing of the source term. The experimental and modeling basis for predicting the uncertainty in the source term magnitude and timing will be reviewed, similar to the review employed in assessing SR2. Gaps in the experimental basis for verifying source-term predictions will be identified and Performance R&D plans reviewed to ensure that the gaps would be addressed. A qualitative comparison of the system source term to the reference Generation III system will be performed. Details for that comparison method will be established by risk and safety crosscut research during the Viability research phase.

SR3-2—Confinement or containment provides robust mitigation of bounding source and energy releases

Definition: Generation IV systems will provide confinement or containment systems that provide sufficient hold-up to reduce offsite doses to levels that preclude harm to the public, for the bounding range of radioactivity source terms and energy releases.

Discussion: Generation IV systems will provide robust, independent mitigation features that will preclude harm to the public even in the event of any significant damage to reactor cores that might be generated by a spectrum of very-low probability event sequences. These systems will be designed to accommodate the release of stored energy in the system, as well as external energy sources. These features will include inherent mechanisms that create long delays for any release, and will make the magnitude of any residual release sufficiently small to meet offsite risk goals.

- *Long and effective holdup.* For reactors, fission product barriers or additional mitigation features independent of the fuel robustness will provide effective retention of any aerosols formed from volatile fission products, and will greatly delay and control any residual release of gaseous fission products. For all facilities, the structural integrity of all mitigation systems will be robust against damage by all stored energy sources present in the system, and the system design will effectively dissipate or eliminate stored energy sources to reduce the probability of damage to mitigation systems. Fission product barriers and mitigation systems will withstand the effects of external events such as earthquakes, fires, and floods. Particular attention will be paid to eliminating the potential for bypass of mitigation systems or confinement.

- *Transport.* Assessment of the transport of radionuclides following fuel damage, will be performed using the same general methods to the same level of quality as residual heat removal modeling described in SR2. Phenomenological models to assess the effectiveness of mitigation features will include time-dependent models for transport and deposition of radionuclides, as well as models for mechanisms where stored energy sources could damage mitigation systems. These models will be validated using data from well-scaled separate effects experiments. While integral experiments can not be performed in the prototypical plant, all transport related integral experiments will be designed to have small and well characterized scaling distortions.

- *Dose.* Dose calculations should be performed using the most technically realistic source terms. Licensing level diffusion calculations should be used to determine the dose at the site boundary to the average individual with no sheltering or evacuation. The dose must be predicted to be well below the U.S. EPA Emergency Protection Guidelines. The acceptability of those Guidelines as an ultimate licensing criteria is questionable, and is therefore only used in the viability assessment. Performance evaluation must employ a rigorous analysis showing attainment of the U.S. NRC Safety Goal Policy (modified for a complete nuclear energy system) as discussed separately below. Systems that rely on a large exclusion zone to accomplish this low dose result will imply requirements for remote siting, and are therefore less preferable than systems employing more robust fuel or inherent mitigation features.

Proposed Evaluation

Long and Effective Holdup

Viability Evaluation: Site boundary doses should be calculated from the scenarios identified in the simplified PRA. All containment/confinement systems and natural phenomena should be considered to demonstrate radioactive releases well below U.S. EPA Protective Action Guidelines.

SR3-3—No additional individual risk.

Proposed Evaluation

Individual Risk Due to Routine Operations

Performance Evaluation: Individual members of the public should be provided a level of protection from consequences of nuclear power system operation such that individuals bear no significant additional risk to life and health

The evaluation will be quantitative, based on PRA results.

Individual Risk Due to Accidents

Performance Evaluation: The risk to an average individual in the vicinity of a nuclear energy facility or prompt fatalities that might result from accidents for which no offsite mitigation measures are taken should not exceed one-tenth of one percent (0.1 percent) of the sum of prompt fatality risks resulting from other accidents to which members of the U.S. population are generally exposed.

The evaluation will be quantitative, based on PRA results.

SR3-4—Societal risk comparable to competing technology.

Societal Risk Due to Routine Operations

Performance Evaluation: Societal risks to life and health from nuclear energy system operation should be comparable to or less than the risks of generating electricity or process commodities by viable competing technologies and should not be a significant addition to other societal risks.

The evaluation will be quantitative, based on PRA results.

Societal Risk Due to Accidents

Performance Evaluation: The risk to the population in areas near nuclear energy facilities of cancer fatalities that might result from nuclear facility operation with no offsite mitigation measures should not exceed one-tenth of one percent (0.1%) of the sum of cancer fatality risks resulting from all other causes.

The evaluation will be quantitative, based on PRA results.

For evaluations, the methodology to be used is a quantitative assessment (Case 3 PRA) with respect to the U.S. NRC Safety Goal Policy Statement for the acceptable level of radioactive risk modified to take into account the complete energy system. The quantitative safety goals above should be met with a reasonable level of uncertainty. A system shown to meet the quantitative evaluation criteria will satisfy the qualitative criteria. Modeling for a spectrum of very-low probability event sequences will provide very high confidence that the nuclear energy system meets the U.S. NRC Safety Goal Policy Statement for the acceptable level of radiological risk, modified to take into account the full fuel and operational cycle. The evaluation criteria would require a small amount of R&D to create a consistent methodology for analysis. However, an attempt at such an analysis was conducted and published as an appendix to NUREG-1150 some years ago. The advantage of such an analysis would be a dramatic demonstration of the level of public safety attained and facilitate perspective for comparison to other energy technologies. It is also postulated that international acceptance of these criteria would be more easily attained than the EPA guidelines.

CRITERIA AND METRICS FOR ECONOMICS GOALS

Goal Statement:

Economics 1 (EC1). Generation IV nuclear energy systems will have a life-cycle cost advantage over other energy sources.

Economics 2 (EC2). Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.

We define a cost metric: (EC1) Average Cost as a function of (EC1-1) Overnight Construction Costs and (EC1-2) Production Costs (including fuel, labor, materials, and waste management and disposal costs). We define a risk metric: (EC2) Capital-at-Risk (during construction) as a function of unit and plant size, (EC1-1), and (EC2-1) Construction Duration. These are discussed below in the order of data collection and calculation; EC1-1, EC1-2, EC2-1, EC2, and EC1. R&D costs are considered elsewhere.

Although much of the quantitative information on these costs and measures will not be available until R&D has been completed, we suggest comparing projected costs at each stage of screening and evaluation with the costs and construction duration of Advanced Light Water Reactors. The goal of the economic roadmap is to develop a business plan for each potentially successful Generation IV technology. Each step of the screening and evaluation process is one step closer to creating this business plan.

Summary table of criteria and metrics.

Criterion		Viability evaluation	Performance evaluation
EC1-1	Low Overnight Construction Costs	Project ranges of overnight construction cost and operating lifetime	Estimate overnight construction cost distribution
EC1-2	Low Production Costs	Project cost ranges for O&M and Fuel (including waste management expenses)	Estimate production and fuel cycle cost distributions per unit of output
EC2-1	Short Construction Duration	Project range of construction duration for first unit and plant	Estimate distribution of construction durations for single and multiple units
EC2	Low Capital-at-Risk	Project range for Capital-at-Risk, optimal plant size, and common costs	Estimate distribution of Capital-at-Risk
EC1	Low Average Cost	Project ranges of average cost and market prices of electricity	Estimate distributions of average cost and market clearing prices

Criteria Definitions

EC1-1—Low Overnight Construction Costs

Definition: Generation IV systems will minimize the cost of constructing generating units.

Discussion: Construction costs have been the most costly aspect of generating electricity from the current generation of nuclear power plants. These costs have been driven by many characteristics. Four of these cost drivers have been:

- The lack of simplicity
- Large structural volumes
- The lack of scalability
- The lack of standardization and modularity.

Here, we suggest using a step-by-step approach to assess overnight capital costs. These include the costs of land, structures, and equipment. Other capital costs, including the costs of financing will be addressed below. (We discuss construction duration in EC2-1.) We suggest identifying information on construction cost drivers to determine whether overnight capital costs for Generation IV technologies will be more or less than for Generation III technologies.

Metric

The midrange of the metric scale has been estimated as follows:

- We rely on NEA, *Projected Costs of Generating Electricity: Update 1998* (Paris: OECD). NEA's Table 7 describes "Nuclear power plant investment costs discounted to the date of commissioning (U.S.$ of 1st July 1996/kWe)." These plants are either commercially available or are expected to be commercially available between 2005 and 2010. We assume these are "Nth-of-a-kind" (NOAK) costs, defined in ORNL, *Cost Estimate Guidelines for Advanced Nuclear Power Technologies* (Oak Ridge, 1993). (Because of different interpretations of what should be included in "contingency," we did not consider contingency in the Final Screening; instead, we focused on developing an understanding of the probability distribution of Generation IV costs.)

- In NEA (1998), the median "base construction cost" is $1,557. The value for the U.S. observation is $1,441. Therefore, we define the midrange of the metric scale for overnight construction cost to be between $1,400 and $1,600/kW. (While inflation has decreased the value of the dollar since 1996, and normally we would inflate the OECD values to 2001 dollars, we believe that the OECD values are still relevant in today's dollars and provide reasonable values with which to benchmark Generation IV technologies.) We propose the following linear scoring for anticipated overnight construction costs. By the time the Viability and Performance evaluations are carried out, the metric scale can be improved with updated information.

EC1-1.

>$2,000/kW	$1,800–2,000/kW	$1,600–1,800/kW	$1,400–1,600/kW	$1,200–1,400/kW	$1,000–1,200/kW	<$1,000/kW

To aid in the estimation of overnight construction costs at each stage of screening and evaluation, consider the following plant characteristics. (**NOTE:** To convert capital costs per kW into costs per MWh see discussion in EC1.)

Viability Evaluation

For the Viability Evaluation, information gathered for the Final Screening should be extended to include projected overnight construction costs, capacity factors, and operating lifetimes. Projecting ranges for each of these would be aided by considering the following plant characteristics.

Project construction cost ranges, lifetimes, and failure probabilities for major plant equipment. Project operating lifetime and capacity factor. To facilitate the determination of generating unit construction costs, project cost ranges for major plant equipment. To facilitate the determination of generating unit lifetimes and capacity factors, project duration to failure for major plant equipment.

Project cost range for each major generating unit structure. To facilitate the determination of generating unit construction costs, project cost range for each generating unit structure as a function of generating unit size.

Describe how generating unit capital costs change with size. Technologies that are easily scaled can meet electricity demand in more markets.

Performance Evaluation

For the Performance Evaluation, information gathered for the Viability Evaluation should be extended to estimate probability distributions for overnight construction costs, capacity factors, and operating lifetimes.

- Estimate cost probability distributions for generating unit equipment.
- Estimate cost probability distribution of generating unit structures.
- Estimate probability distributions for operating lifetime and capacity factor.
- Estimate probability distribution for total construction cost per unit of output.

With probability distributions for the cost of equipment and structures and the capacity factor, estimate probability distribution construction cost per unit of output. Note any co-variances between costs, operating lifetime, and capacity factor.

EC1-2—Low Production Costs

Definition: Generation IV systems will minimize production costs.

Discussion: This section addresses all nondepreciable production inputs, including the cost of waste management. (Depreciable costs for equipment with a service life of more than one year, are considered capital additions and are included in EC1.) While fuel inputs vary with electricity production for most generating technologies, nuclear fuel accounting is more complex. Therefore, although it has many characteristics of a depreciable capital asset, we treat it as a production cost. Also, while budgets and labor contracts are set annually (or over longer periods), we treat all nondepreciable operations and maintenance (O&M) expenditures as production costs. In the Final Screening evaluators compared O&M plus fuel (including waste management costs) to Generation III experience and projections. The Viability and Performance Evaluation should improve on these estimates.

Metric

The midrange of the metric scale has been estimated as follows:

- We rely on NEA (1998) Table 16 “Projected generation costs calculated with generic assumptions at 10% p.a. discount rate.” The median “O&M + Fuel” (including waste management) projection is \$13.74/MWh, the mean is \$14.61/MWh, the standard deviation is \$5.10, and the U.S. estimate is \$14.78/MWh. We define the midrange of production costs to be between \$14.00 and \$16.00/MWh.

- These costs represent approximately \$9/MWh for O&M and \$6/MWh for fuel (including \$1/MWh for spent nuclear fuel management). Therefore, if the power plant is likely to have Fuel and O&M costs that diverge from these values, explain how each of these costs is similar to or different from these reference values. Also, we assume that all plants have a lifetime capacity factor of 90%. By the time the Viability and Performance evaluations are carried out, the metric scale can be improved with updated information.

We propose the following linear scoring for anticipated production costs:

EC1-2.

>\$20/MWh	\$18–20/MWh	\$16–18/MWh	\$14–16/MWh	\$12–14/MWh	\$10–12/MWh	<\$10/MWh

Viability Evaluation

Estimate cost range for fuel requirements per unit of output. The cost of fuel depends on the cost of the raw material, the cost of processing, the cost of enrichment (if applicable), the cost of fuel fabrication, the capital cost of financing the fuel cycle, and the cost of spent nuclear fuel management. Estimate the range of cost for fuel to generate a unit of energy output.

Identify cost range for operations and maintenance. The cost of operations and maintenance (O&M) depends on the cost of highly trained labor and supervision, the cost of continuous training, the cost of regulatory compliance (including engineering and health physics), and the cost of security. Also included are administrative and general overheads such as insurance. Many of these costs are fixed on an annual basis, therefore estimate the range of annual costs for O&M. For guidance on O&M costs, see ORNL (1993, Section 4.3).

Estimate ranges of amounts of chemical, radioactive, or mixed wastes. Technologies with smaller, less toxic, and easier to manage waste volumes should have lower waste management costs.

Performance Evaluation

Identify cost distribution for fuel requirements per unit of output. Specify the probability distribution for the cost of fuel requirements per unit of output. Describe how this distribution changes with the size of the generating unit and the number of generating units.

Identify cost distribution for operations and maintenance per unit of output. Specify the probability distribution for O&M cost per unit of output. Describe how this distribution changes with the capacity factor of the generating unit and the number of generating units.

Estimate expected costs of managing chemical, radioactive, or mixed wastes per unit of output. Technologies with smaller, less toxic, and easier to manage chemical and radioactive wastes should have lower waste management costs.

EC2-1—Short Construction Durations

Definition: Generation IV systems will minimize construction duration.

Discussion: Nonconstruction capital costs are dominated by interest during construction (IDC), which depends primarily on construction duration (and expenditure profile) and the cost of capital charged by financial markets. Construction expenditures are addressed in EC1-1. The cost of capital is addressed in EC2. Here, we address construction duration—the time between "Construction Start" (defined by IAEA as "Date when first major placing of concrete, usually for the base mat of the reactor building, is done.") to Commercial Operation (defined by the IAEA as "Date when the plant is handed over by the contractors to the owner and declared officially to be in commercial operation.") See, for example, IAEA, *Nuclear Power Reactors in the World* (April 2001). By the time the Viability and Performance evaluations are carried out, the metric scale can be improved with updated information.

Metric

The midrange of the metric scale has been estimated as follows:

- We rely on the construction duration of the ABWR in Japan of 48 months within a 10-month range. We assume linear scoring in a range between about 2 and 6 years.

EC2-1.

>75 months	65–75 months	55–65 months	45–55 months	35–45 months	25–35 months	<25 months

Viability Evaluation

Outline the construction sequence for the generating unit and identify construction duration uncertainties. Estimate construction duration for the generating unit.

Note: There are three phases in nuclear plant construction. Phase 1 includes site preparation and excavation, design engineering, and equipment procurement. Phase 2 begins with "construction start" and ends with start of fuel loading. Phase 3 includes fuel loading and safety testing. Discuss the length of each phase for the first unit and subsequent units. Estimate the durations of Phase 2 and 3 (during which most of the construction expenditures are spent).

Because of shorter construction durations with mass production, technologies with more subsystems that can be produced in central locations should be quicker to build. Describe how modular production will shorten construction duration.

To understand construction duration uncertainties, define the critical path for generating unit construction.

Performance Evaluation

Estimate construction duration probability distribution.

EC2—Low Capital-at-Risk

Definition: Generation IV systems will minimize Capital-at-Risk.

Discussion: During the period of construction, typically the owner is responsible for financing plant construction costs. Capital-at-Risk measures the total accumulated investment in the project during the construction period. It includes in constant dollars both the overnight cost (the physical cost of building the plant and indirect costs) and IDC, which depends primarily on construction duration (and expenditure profile) and the cost of capital charged by financial markets. Capital-at-risk measures the total amount of capital that must be obtained to finance the complete construction of the first unit—until the project is capable of generating power and earning a return. Both bankers (providing loans) and private investors (providing equity) are interested in this measure because it indicates the total funding that needs to be dedicated to a specific project before revenues are generated. In general, the lower the total investment required, the lower the risk.

For single-unit plants, the capital-at-risk is equal to all overnight construction costs plus IDC. For multiple-unit plants Capital-at-risk includes common costs, overnight construction costs, and IDC on the first unit. Therefore, to calculate capital-at-risk, evaluators must identify the anticipated size of the generating unit and size of the plant. Adjustment to EC1-1 must be made to account for common costs.)

IDC and the present value of other capital costs is a function of the cost of capital. Throughout this analysis we use real costs, and thus we use real costs of capital, abstracting from the general level of inflation. As in ORNL (1993), we assume the escalation rate is equal to the inflation rate. This is equivalent to assuming that real “escalation during construction” is zero.

Finally, risk premiums charged to owners of nuclear power plants after construction reflects the probability of losing asset value due to an accident (see discussion associated with SR1-1) or regulatory action, and the risk of default on capital obligations.

Metric

The midrange of the metric scale is estimated as follows:

1. First, we assume a 10% real discount rate (following suggested practice by the U.S. Office of Management and Budget; this discount rate should decrease as financial markets become more familiar with Generation IV technologies).

2. Second, we rely on NEA (1998) Table 7. In addition to the "base construction cost," the table presents estimates of "Contingency, Interest during construction, Major refurbishments, and Decommissioning" at discount rates of 5% and 10%. (We discuss refurbishments and decommissioning in EC1.) To aid in the estimation of IDC, we use the following "rule of thumb."

   We assume a uniform spending rate. So, IDC is approximately equal to the discount rate times one-half the construction duration. For example, with a 10% discount rate, if the construction duration were 4 years, IDC would be approximately 20% of the construction cost. If construction costs were $1,500, then IDC would be $300. Common costs of $150M are assumed.

   Capital-at-Risk = [(First Unit Size in kW · Overnight Cost/kW) + Common Costs] (1 + [10% · (Construction Duration/2)])

   Considering a 1,000 MW (single-unit) ALWR as the standard, with a $1,500/kW overnight construction cost and a construction duration of 4 years, the Capital-at-Risk would be

   1,000 MW · $1,500/kW · (1 + 20%) = $1,800M .

   The highest and lowest estimates for overnight construction costs and construction duration will be combined to obtain the range for Capital-at-Risk.

EC2.

>$3,000M	$2,500–3,000M	$2,000–2,500M	$1,500–2,000M	$1,000–1,500M	$1,000–500M	<$500M

By the time the Viability and Performance evaluations are carried out, the metric scale can be improved with updated information.

Viability and Performance Evaluations

Identify licensing uncertainties for power and fuel systems. Because licensing and regulatory uncertainties influence construction duration and thus directly and indirectly the capital markets perception of financial risk (increasing risk premiums for more risky technologies), technologies with fewer licensing uncertainties pending during the Viability evaluation should have lower risk premiums imposed by financial markets.

Compare financial risk with other energy projects. Evaluate risk premium on debt and equity charged to current owners of nuclear power plants; perform sensitivity analysis of total costs with respect to the cost of capital.

EC1—Low Average Cost

Definition: Generation IV systems will be have average costs lower than the market clearing price of electricity.

Discussion: This section addresses the bottom line. Cost estimates per unit of electricity for each cost category are summed by the software to determine the life-cycle cost per unit of energy and scored with respect to the reference. Some nuclear technologies can integrate the production of electricity with the production of other commercial products. The Viability and Performance evaluations will assess the affect of these other commercial products on competitiveness.

Metric

The midrange for the metric scale has been determined as follows:

Determine Average Cost: Average Cost is equal to the sum of:

- (1.1) Overnight Construction Costs per MWh (from EC1-1)
- (1.2) Interest During Construction per MWh (see below)
- (2) Production Costs per MWh (from EC1-2)
- (3) Capital Additions per MWh (see below)
- (4) Contributions per MWh to a Nuclear Decommissioning Trust Fund (or equivalent, see below).

1. **Overnight Construction Costs Plus IDC per MWh**: Here, EC1-1 is converted into a Capital Cost per MWh. This is done by multiplying overnight construction costs and IDC by the Capital Recovery Factor (CRF) and dividing by the number of MWh generated annually. (We assume that all plants have an 90% Capacity Factor.)

   Capital = [(Construction Cost + IDC) · CRF] / (CF · 8760)

   $$\text{CRF} = [r \cdot (1 + r)^T] / [(1 + r)^T - 1] = (0.1 \cdot 1.1^{40}) / (1.1^{40} - 1) = 10.2\%$$

   $$\text{Capital} = \underline{[(\text{Construction Cost} \cdot [1 + (10\% \cdot \text{Construction Duration} \cdot 0.5)]) \cdot 10.2\%]}\ (90\% \cdot 8760)$$

   $$\text{Capital} = (\$1{,}800{,}000/\text{MW} \cdot 10.2\%)/(90\% \cdot 8760) = \$23.29/\text{MWh}$$

   Note: The capital recovery level per MWh for the Overnight Construction Cost (without IDC) would be $19.40 in this example.

2. **Production Costs**: Production Costs were calculated on a per MWh basis in EC1-2. They were compared with $15/MWh.

3. **Capital Additions:** Capital additions include all production costs that have a productive life of more than one year. We assume Capital Additions of the Generation IV plant are $2/MWh.

4. **Decommissioning Costs:** The implicit assumption in NEA (2000) for decommissioning U.S. plants is one-third of the construction cost, discounted 40 years to the start of operations. We adopt this assumption. If construction costs were $1,500/kW, decommissioning costs would be $500/kW. These costs must be accumulated over the life of the plant, T (e.g., 40 years), so that decommissioning could begin at the end of the operating life. We assume that the return on Nuclear Decommissioning Trust Funds is 5% (real).

   $$\text{Decomm} = (1/3 \cdot \text{Construction Cost}) \cdot (r / [(1 + r)^T - 1])/(\text{CF} \cdot 8760)$$

   $$\text{Decomm} = (1/3 \cdot \$1{,}500) \cdot (0.05 / [(1.05)^{40} - 1])]/(90\% \cdot 8760) = \$0.52/\text{MWh}\ .$$

In the example values used here, Average Cost is equal to $23.29/MWh plus $15/MWh plus $2/MWh plus $0.52/MWh, or $40.81/MWh. These are much higher than the reference market-clearing price. Therefore, for Generation IV costs to be competitive, they must be significantly lower than ALWR costs in one or more cost categories.

We use a $20/MWh range of electricity. Scoring is linear within this $20 range.

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>$42/MWh	$42–38/MWh	$38–34/MWh	$34–30/MWh	$30–26/MWh	$26–22/MWh	<$22/MWh

By the time the Viability and Performance evaluations are carried out, the metric scale can be improved with updated information.

Viability Evaluation

Identify revenue range from all commercial outputs. Estimate the range of total revenues from all commercial outputs including electricity. Technologies with higher estimated revenues per unit of output should be more profitable.

Project cost ranges, lifetimes, and failure probabilities for major plant equipment. To facilitate the determination of generating unit capital additions, project duration to failure and costs for replacing major plant equipment.

Performance Evaluation

Estimate probability distribution of the net cost per unit of output. Estimate the probability distribution of total net cost to produce all commercial outputs. Technologies with lower expected net costs per unit of output should be more profitable.

Estimate probability distribution for decommissioning cost. Estimate decommissioning costs. Identify special decommissioning requirements such as decommissioning liquid metals. Compare with Generation II decommissioning cost experience and projected Generation III decommissioning costs.

Estimate the probability distribution of total capital costs and annual financing payments as a function of construction cost and time, operating lifetime, amortized decommissioning costs, and the cost of capital. Because financial risk is a function of total capital costs and annual capital payments (including payments to debt and equity and to a Nuclear Decommissioning Trust Fund), technologies with lower expected total capital costs and annual payments as a percent of anticipated revenues should have a lower cost of capital.

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